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TITLE: DOES LACTATION MITIGATE TRIPLE NEGATIVE/BASAL BREAST CANCER PROGRESSION?

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14. ABSTRACT
Young Black women develop and die more from aggressive forms of breast cancer compared to young White women. Recent data show increased risk of basal-like breast cancer with increased childbearing in Black women. Breast cancers associated with a recent pregnancy are more likely to be metastatic. We predict that aggressive breast cancers are promoted by a recent pregnancy. We developed a murine mammary intraductal model to examine effects of host reproductive status on the tumor suppressive myoepithelial cell layer with respect to tumor progression. Our data, demonstrating that DCIS lesions with an intact myoepithelial cell layer display progressive loss of specific myoepithelial cell markers, suggest that the myoepithelium is compromised prior to DCIS progression to invasive disease. The loss of p63 was identified as an early indicator of compromised myoepithelium. Further, our data suggests that this protective layer may be maintained by tumors formed during pregnancy lactation cycle, but may be preferentially compromised by tumors formed in postpartum involuting mammary glands.Our preclinical model of human breast cancer provides a rigorous approach to study effects of reproductive state on DCIS progression. Our model could aid research of early disease progression, a requisite for research focused on breast cancer prevention and inhibition of local invasion. Further, this model may provide a unique opportunity to address and study tumor growth disparities among ethnically diverse women.

15. SUBJECT TERMS
Triple negative/basal breast cancer, pregnancy-associated breast cancer, young African American women, pregnancy, lactation, myoepithelial cell layer

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INTRODUCTION

Young African American women have an increased risk of developing aggressive forms of breast cancer (i.e. triple negative/basal-like) than young non-Hispanic white women. Recent epidemiological data show increased risk of basal-like breast cancer with increased childbearing and lack of breastfeeding in African American women [1, 2]. Breast cancers associated with a recent pregnancy (pregnancy-associated breast cancer) are more likely to be metastatic [3]. **We predict that the triple negative/basal-like breast cancer subtype is promoted by a recent pregnancy, but mitigated by lactation.**

We have previously reported the development of our murine intraductal mammary model [4, 5] to examine the effect of host reproductive status on the progression of early stage human breast cancer. Our model delivers human mammary tumor cells (MCF10ADCIS.com) directly through the intact mouse teat into the correct anatomical location for ductal carcinoma in situ (DCIS) without surgical manipulations. Using the MCF10ADCIS.com model to assess the effects of host reproductive status on DCIS progression, we found that DCIS progression to locally invasive disease occurred with progressive loss of myoepithelial cell differentiation markers. The loss of p63 was identified as an early indicator of compromised myoepithelium. Further, our data suggest that the protective myoepithelial cell layer may be preferentially compromised by tumors formed in postpartum involuting mammary glands but maintained by pregnancy and lactation.

Our murine mammary intraductal model of human breast cancer provides a rigorous approach to study early stage-tumor progression, and is well suited to study the effect of the host reproductive state on DCIS progression. Since occult tumors in women develop within ducts, we propose that this teat injection model will aid research of early disease progression, a requisite for research focused on breast cancer prevention and inhibition of local invasion. Further, this model may provide a unique opportunity to address and study tumor growth disparities among African American and non-Hispanic white women.

BODY

STATEMENT OF WORK AND ACCOMPLISHMENTS

Specific Aim 1 – Determine if pregnancy and/or involution, in the absence of lactation, confer tumor promotion of triple negative/basal breast cancer.

Task 1 – Develop intraductal xenograft mouse model of triple negative/basal breast cancer during pregnancy.

Months 1-12

1a. Randomize 48 SCID mice, 5-weeks of age, into 2 groups (nulliparous control and day 19 of gestation) with 12 mice/group for each triple negative/basal cell line (MCF10ADCIS.com and MDA-MB-157). Task completed for MCF10ADCIS.com cell line.

1b. Intraductally inject either MCF10ADCIS.com or MDA-MB-157 into left and right 3rd and 4th mammary glands of all mice at age 5 weeks. Task completed for MCF10ADCIS.com cell line.

1c. Breed mice except the nulliparous controls at 10 weeks of age. Task completed MCF10ADCIS.com cell line.

1d. Euthanize pregnant mice on day 19 of gestation along with age-matched nulliparous controls. Tumor "age" at this stage is 8 weeks. Task completed for MCF10ADCIS.com cell line.

1e. Harvest the left and right 3rd and 4th mammary glands 8 weeks post-injection and fix in formalin for histology. Task completed for MCF10ADCIS.com cell line.

Months 12-24

1f. Submit manuscript characterizing the effect of pregnancy and involution on early stages of tumor progression (currently in progress).

1g. Submit manuscript describing the technical aspects of the intraductal injection method (currently in progress). Task completed (resubmission in progress).

1h. Continue characterizing changes in the expression of myoepithelial cell markers with respect to tumor progression in the pregnant and nulliparous host environments (currently in progress).

1i. Develop intraductal xenograft mouse model of triple negative/basal breast cancer during pregnancy using the MDA-MB-157 cell line. Currently in progress using HCC70 cell line (see explanation in Major Updates for Tasks 1a-1e).

Major Updates for Tasks 1a – 1e:

1. In our intraductal preclincal model of human breast cancer, MCF10ADCIS.com cells undergo evolution from stages of DCIS development (hyperplasia, solid, cribriform, papillary, and comedo) to invasive lesions in both the nulliparous and pregnant host environments as assessed by hemotoxylin and eosin histology (Figure 1).

2. Tumor burden was not increased in the pregnant group compared to their respective nulliparous controls (Figure 2A). Ki67 proliferative index (Figure 2B) is increased in tumors from the nulliparous group compared to normal cells ($^{\dagger}p = 1.956E-06$). Interestingly, there was no difference in Ki67 proliferative index between tumors and normal cells in the pregnant group ($p = 0.1256$). There was a slight but significant decrease in Ki67 proliferative index in tumors from the pregnant group compared to tumors from their respective nulliparous controls ($^{\dagger\dagger}p = 0.0441$). As expected, Ki67 proliferative index was much higher in normal cells from the pregnant group compared to nulliparous controls ($^{\dagger\dagger\dagger}p = 1.407E-05$).

3. Although MCF10ADCIS.com cells were initially characterized as being triple negative [6], some MCF10ADCIS.com tumors re-express estrogen receptor (ER) in vivo (Figure 3A). There was a slightly lower but significant ($*p = 0.0697$) expression of ER in the pregnant group compared to their respective nulliparous controls (Figure 3B). Thus, tumors in the pregnant group appear to be less proliferative and have slightly lower ER expression than tumors in their respective nulliparous controls, suggesting that the hormonal milieu of pregnancy may have an effect on certain mechanisms of tumor progression.

4. In the pregnant host environment myoepithelial cells surrounding DCIS lesions have higher expression of smooth muscle actin and calponin compared to their respective nulliparous controls, suggesting a more differentiated phenotype. Myoepithelial cell expression of p63, a putative tumor suppressor, is lost early during DCIS progression independent of group (Figure 4 and Table 1).

Major Updates for Tasks 1f – 1i, Year 2:

1. Submitted manuscript describing the technical aspects of the intraductal injection method (see Appendices).

2. Levels of Cyclooxigenase-2 (COX2), an enzyme responsible for the formation of prostaglandins during inflammatory response, were not increased in the pregnant group compared to respective nulliparous controls (Figure 1).

3. Using our intraductal preclinical model of human breast cancer, we obtained and tested another other triple negative breast cancer cell lines, HCC70 (Figure 2A), in addition to the proposed MDA-MB-157 cell line (Figure 2B). The HCC70 cell line provided the most robust results, developing tumors throughout the mouse mammary gland and displaying certain characteristics of human DCIS in vivo.

4. In an effort to understand the role of the mammary myoepithelial cell layer with respect to tumor progression, we performed a detailed analysis on early stages of tumor progression in our mammary intraductal model. Nulliparous mouse mammary glands were intraductally injected with MCF10ADCIS.com cells and mammary glands were harvested 96 hours, 4 weeks, or 10 weeks post injection. Mammary ducts contain more normal (3-4 cell tumor cell bolus) and hyperplastic lesions at 96h post-injection (Figure 6A). By 4 weeks post injection, the mammary gland contains a heterogeneous display of tumor progression but has shifted to more DCIS lesions (Figure 6B). At 10 weeks post injection, tumor progression has shifted to more DCIS and invasive lesions (Figure 6C).

5. Assessed the myopepithelial cell layer during early stages of tumor progression (Figure 7). The myoepithelial cell layer is compromised early during DCIS progression of MCF10ADCIS.com tumors; the tumor suppressor p63 is lost by 96 hours post injection, while smooth muscle actin (SMA) and calponin are intact. By 4 weeks post injection, all myoepithelial cell markers are markedly decreased (Figure 7).

6. Confirmed our initial data from Year 1 with a more detailed analysis on the effect of pregnancy on the myoepithelial cell layer (Figure 8). Our data suggests that the myoepithelial cell layer around tumors may not be compromised during pregnancy, suggesting that pregnancy may maintain its tumor suppressive phenotype.

Major Updates for Tasks 1a – 1i, Year 3:

1. Resubmit manuscript describing the evidence for progression of mammary myoepithelial cell loss with tumor progression (currently in progress).

2. Performed a more stringent statistical analysis (one-way ANOVA) to examine the effect of pregnancy on the myoepithelial cell layer. Calponin expression in myoepithelial cells surrounding tumors exposed to pregnancy were significantly higher compared to nulliparous controls (Figure 1).

Months 1-12

1f. Harvest the liver, lung, kidney and brain tissues for determination of metastatic lesions by both IHC and PCR based techniques. Task completed for MCF10ADCIS.com cell line.

Major Updates for Task 1f:

1. We currently have paraffin embedded tissue from liver, lung, kidney and brain from both nulliparous and pregnant groups and lung serial sections cut from nulliparous and pregnant groups.

2. We have also collected frozen tissue from liver, lung, kidney and brain from both nulliparous and pregnant groups to assess metastases by QRT-PCR analysis.

Months 12-24

1j. Harvest the liver, lung, kidney and brain tissues for determination of metastatic lesions by both IHC and PCR based techniques. Task completed for MCF10ADCIS.com cell line.

Major Updates for Task 1j:

We did not detect lung (or liver?) metastasis at 4 weeks post-intraductal injection in the pregnant group.

Proposed Work for Task 1j, Year Three:

Since it appears that pregnancy may have a protective effect on tumor progression, no further work with respect to metastasis is proposed for Year Three.

Task 1A –Develop intraductal xenograft mouse model of luminal A breast cancer during pregnancy.

Months 12-24

1a. Randomize 9 SCID mice, 5-weeks of age, into 3 groups (no pellet control, estrogen pellet, pregnancy/no pellet) with 3 mice/group for each luminal A cell line (MCF7.com and T47D). Task completed.

1b. Intraductally inject either MCF7 or T47D into left and right 3rd and 4th mammary glands of all mice at age 5 weeks and insert estrogen pellets. Task completed.

1c. Breed mice except the nulliparous controls at 10 weeks of age. Task completed.

1d. Euthanize pregnant mice on day 19 of gestation along with age-matched nulliparous controls. Tumor "age" at this stage is 8 weeks. Task completed.

1e. Harvest the left and right 3rd and 4th mammary glands 8 weeks post-injection and fix in formalin for histology. Task completed.

1f. Harvest the liver, lung, kidney and brain tissues for determination of metastatic lesions by both IHC and PCR based techniques. Task completed.

Major Updates for Tasks 1A, 1a-1f:

1. We determined if lack (or minimal expression) of both estrogen receptor (ER) and progesterone receptor (PR) in MCF10ADCIS.com cells, and subsequent lack of response to pregnancy hormones, attributed to the lack of tumor burden increase during pregnancy by injecting luminal A cell lines (MCF7 and T47D in the presence and absence of estrogen supplementation (see University of Colorado IACUC amendment approval letter in Appendices).

2. All groups of female SCID mice were injected with either or both MCF7 cells (right 4th inguinal mammary gland) and T47D cells (left 4th inguinal mammary gland) and divided into three groups: Group 1 – no pellet control; Group 2 – estrogen pellet; Group 3 – pregnancy/lactation, no estrogen pellet.

a. Group 2 received estrogen pellets (0.72 mg/pellet) at the time of injection.
b. Group 3 did not receive estrogen pellets and were bred 5 days post-injection.
c. Mammary glands from all groups were harvested at the same time as Group 3 (~3 weeks post injection), which were euthanized 2 days post-lactation.

3. Initial hemotoxylin and eosin (H&E) and fluorescent in situ hybridization anaylsis (FISH) analysis showed no T47D tumors in the mammary glands from Group 1 (Figure 3).

4. No T47D tumors were evident in mammary glands from Group 2 (Figure 4A), whereas MCF7 tumors formed in mammary glands from Group 2 (Figure 4B). Although no T47D tumors were evident in Group 2 (Figure 4A), a few developing tumors were present in some mammary ducts (Figure 5A). Similarly, there were areas of putative MCF7 tumor development in Group 3 (Figure 5B), but they were not as prominent as those in Group 2 (Figure 4B). Along with the tumor burden and proliferation data from Year 1, these data further suggest that pregnancy has a protective effect with respect to tumor progression.

Proposed Work for Task 1A, Year Three:

Since it appears that pregnancy may have a protective effect on tumor progression, no further work with respect to luminal A breast cancer is proposed for Year Three.

Task 2 – Develop our intraductal xenograft model of pregnancy associated breast cancer to determine whether the involution microenvironment alone promotes triple negative/basal metastasis. Months 1-12

Months 1-12

1a. Randomize 48 SCID mice, 5-weeks of age, into 2 groups (nulliparous control and day 19 of gestation) with 12 mice/group for each triple negative/basal cell line (MCF10ADCIS.com and MDA-MB-157). Task completed for MCF10ADCIS.com cell line.

1b. Breed mice at 5 weeks of age except the nulliparous controls. After parturition, normalize pups to 8, and wean at 9 days of parturition to initiate involution. Task completed for MCF10ADCIS.com cell line.

1c. Intraductally inject either MCF10ADCIS.com or MDA-MB-157 into left and right 3rd and 4th mammary glands of mice 2 days post-weaning (also inject age-matched nulliparous controls). Task completed for MCF10ADCIS.com cell line.

1d. Euthanize all mice 8 weeks post-injection. Tumor "age" at this stage is 8 weeks. Task completed for MCF10ADCIS.com cell line.

1e. Harvest the left and right 3rd and 4th mammary glands 8 weeks post-injection and fix in formalin for histology. Task completed for MCF10ADCIS.com cell line.

Months 12-24

1f. Submit manuscript characterizing the effect of pregnancy and involution on early stages of tumor progression (currently in progress).1g.Continue characterizing changes in the expression of myoepithelial cell markers with respect to tumor progression in the involution and nulliparous host environments. Task completed for MCF10ADCIS.com cell line.

1g. Develop intraductal xenograft mouse model of triple negative/basal breast cancer during involution using the HCC70 cell line. Currently in progress (See Major Updates for Task 1 for explanation of new cell line addition).

Major Updates for Task 2 (1a – 1e):

1. In our intraductal preclinical model of human breast cancer, MCF10ADCIS.com cells undergo evolution from stages of DCIS development (hyperplasia, solid, cribriform, papillary, and comedo) to invasive lesions in both the nulliparous and involution host environments as assessed by hemotoxylin and eosin histology (Figure 5A) and fluorescent in situ hybridization analyses (Figure 5B).

2. Tumor burden is greater in the involution group compared to their respective nulliparous controls (Figure 6A). Ki67 proliferative index (Figure 6B) is increased in tumors from both the nulliparous and involution groups compared to normal cells ($^{*}p = 5.859E-08$ and 1.082E-07, respectively). There was no significant difference in Ki67 proliferative index between tumors in the nulliparous group compared to the involution group ($p = 0.1737$). However, there was a decrease in Ki67 proliferative index in normal cells from the involution group compared to normal cells from their respective nulliparous controls ($^{**}p = 0.021$).

3. There was no difference in ER expression in tumors from the involution group compared to their respective nulliparous controls (*p = 0.3009) (Figure 7).

4. In myoepithelial cells surrounding post-partum involution group DCIS lesions, smooth muscle actin expression is high, but calponin is lost at a higher frequency, suggesting a less differentiated phenotype. Myoepithelial cell expression of p63, a putative tumor suppressor, is lost early during DCIS progression independent of group (Figure 8 and Table 2). Taken together with the pregnancy data (Figure 4 and Table 1) SMA positivity remains relatively stable, suggesting that the actin biostructure may be a later barrier broken in tumor progression. In contrast, p63 positivity appears to be lost first in all tested microenvironments and calponin positivity appears to lost preferentially in the post-partum involution environment. These data may reflect key differences in the influence of these reproductive states on tumor progression.

Major Updates for Task 2 (1f – 1g), Year 2:

1. Levels of Cyclooxigenase-2 (COX2), an enzyme responsible for the formation of prostaglandins during inflammatory response, were increased in the involution group compared to respective nulliparous controls (Figure 9).

2. Developed intraductal xenograft mouse model of triple negative/basal breast cancer during involution using the HCC70 cell line (currently in progess).

3. Initiated an additional objective to analyze tumor cell escape during involution. In our current involution model, tumor cells are injected during early stages of involution (Day 2) when the mammary gland is actively remodeling. This process could allow tumor cells to readily escape mammary ducts. We assessed whether "pre-existing" MCF10ADCIS.com tumor cells have the ability to escape the mammary ducts at the onset of involution (currently in progress).

a. Two groups of female SCID mice were injected with MCF10ADCIS.com cells (both right and left 4th inguinal mammary glands): Group 1 – nulliparous control; Group 2 – early involution group.
b. Group 2 females were bred 5 days post-injection. Pup litters were normalized to eight pups 1 day postpartum.
c. Mammary glands from Group 2 were harvested at involution day 6. Mammary glands from Group 1 were harvested at the same time.

4. Confirmed our initial data from Year 1 with a more detailed analysis on the effect of involution on the myoepithelial cell layer (Figure 10). Our data suggests that the protective myoepithelial cell layer may be compromised by tumors formed in post-partum involution mammary glands.

Major Updates for Task 2 (1f – 1f), Year 3:

1. Analysis of mammary glands from the tumor cell escape during involution experiment (see Major Update number 3, Year 2) showed no clear evidence of tumor cells outside of the mammary ducts.

2. In myoepithelial cells surrounding tumors in the involution group, p63 expression is significantly less than calponin, which is significantly less than SMA. In contrast, the levels of SMA and calponin in the nulliparous groups are not statistically significant (Figure 2). These data show sequential loss of expression of p63, calponin and SMA and that myoepithelial cells are compromised by tumors formed in post-partum involution mammary glands.

Major Updates for Task 2 (1g), Year 3:

1. In our intraductal preclinical model of human breast cancer using HCC70 cells, tumor burden in the involution group was much lower than that of the nulliparous group (Figure 3A). This is in contrast to tumors formed from MCF10ADCIS.com cell, which exhibit a significantly higher tumor burden compared to nulliparous controls.

2. Performed an initial assessment of myoepithelial cells surrounding HCC70 DCIS lesions in mammary glands from nulliparous mice. Our data show higher expression levels of smooth muscle actin and calponin and decreased p63 expression, suggesting that HCC70 cells may not form aggressive lesions.

Months 1-12

1f. Harvest the liver, lung, kidney and brain tissues for determination of metastatic lesions by both IHC and PCR based techniques. Task completed for MCF10ADCIS.com cell line.

Major Updates for Task 2 (1f):

1. We did not detect lung metastasis at 4 weeks post-intraductal injection in neither the involution nor nulliparous groups by QRT-PCR (Figure 9). We also did not detect lung or liver metastasis at 8 weeks post-intraductal injection by FISH analysis (Figure 10).

Proposed Work for Task 2 (1f), Year Two:

1. Determine if metastasis occurs in the intraductal injection model by increasing "tumor age" in the involution and nulliparous host environments.

Months 12-24

1i. Determine if metastasis occurs in the intraductal injection model by increasing "tumor age" in the involution and nulliparous host environments.

Major Updates for Task 2 (1i):
Although some large tumors formed ($2cm^3$), we did not detect lung or liver metastasis at 10-12 weeks post-intraductal injection.

Proposed Work for Task 2 (1i), Year Three:
No further work with respect to metastasis is proposed for Year Three.

Task 3 – Develop a two-hit pregnancy/involution tumor promotional intraductal xenograft model in the absence of lactation. Months 12-24

1a. Randomize 48 SCID mice, 8-weeks of age, into 2 groups (nulliparous control and day 19 of gestation) with 12 mice/group for each triple negative/basal cell line (MCF10ADCIS.com and MDA-MB-157). Task completed for MCF10ADCIS.com cell line with 18 mice.

1b. Breed mice at 8 weeks of age except the nulliparous controls. Task completed for MCF10ADCIS.com cell line with 18 mice.

1c. Intraductally inject either MCF10ADCIS.com or MDA-MB-157 into left and right 3rd and 4th mammary glands of mice at day 1 of pregnancy (also inject age-matched nulliparous controls). Task completed for MCF10ADCIS.com cell line with 18 mice.

1d. Remove pups at parturition and allow mammary glands to involute 1 week and fully regress 4 weeks. Task completed for MCF10ADCIS.com cell line with 18 mice.

1e. Euthanize all mice at 4 weeks full-regression. Tumor "age" at this stage is 8 weeks. Task completed for MCF10ADCIS.com cell line with 18 mice.

1f. Harvest the left and right 3rd and 4th mammary glands and fix in formalin for histology. Task completed for MCF10ADCIS.com cell line with 18 mice.

1g. Harvest the liver, lung, kidney and brain tissues for determination of metastatic lesions by both IHC and PCR based techniques. Task completed for MCF10ADCIS.com cell line with 18 mice.

Major Updates for Task 3:

1. Due to technical difficulties with the particular batch of MCF10ADCIS.com cells, we did not get a sufficient tumor take rate. Only 3 of the 18 injected mammary glands developed tumors in this particular experiment.

Proposed Work for Task 3, Year Two:

1. Complete intraductal injections with remaining proposed number of mice during pregnancy and involution in the absence of lactation.

2. Evaluate tumor latency, growth, burden and multifocal nature of tumor.

2. Characterize changes in the expression of myoepithelial cell markers with respect to tumor progression in absence of lactation.

3. Analyze evidence of metastasis by QRT-PCR, IHC and FISH.

Task 4 – Manuscript Preparation. Months 18-24

Proposed Work for Task 4, Year Two:

1. Submit manuscript characterizing the effect of pregnancy and involution in the absence of lactation on tumor progression (currently in progress)

Specific Aim 2 – Determine if lactation mitigates promotional effects of pregnancy/involution on triple negative/basal-like breast tumor progression.

Task 1 – Develop an intraductal xenograft mouse model of triple negative/basal-like breast cancer to determine if length of lactation mitigates tumor promotion. Months 24-36

1a. Randomize 60 SCID mice, 8-weeks of age, into 5 groups of increasing lengths of lactation with12 mice/group for each triple negative/basal cell line (MCF10ADCIS.com and MDA-MB-157). Task completed for MCF10ADCIS.com cell line for Group 1 (7 mice), Group 5 (7 mice), and nulliparous controls (6 mice).

Group #	Tumor cell Injection	Gestation (weeks)	Lactation (weeks)	Post-partum involution (weeks)	Full Regression (weeks)	End of study tumor "age" (weeks)
1	P1	3	0	1	4	8
2	P1	3	0.28 (2 days)	1	4	8
3	P1	3	1.5	1	2.5	8
4	P1	3	3	1	1	8
5	P1	3	4	1	0	8

1b. Breed mice at 8 weeks of age except the nulliparous controls. Task completed for MCF10ADCIS.com cell line for Group 1 (7 mice) and Group 5 (7 mice).

1c. Intraductally inject either MCF10ADCIS.com or MDA-MB-157 into left and right 3rd and 4th mammary glands of mice at day 1 of pregnancy (also inject age-matched nulliparous controls. Task completed for MCF10ADCIS.com cell line for Group 1 (7 mice), Group 5 (7 mice), and nulliparous controls (6 mice).

1d. Euthanize animals at various stages of full gland regression for tumor "age" to be 8 weeks throughout entire study. Task completed for MCF10ADCIS.com cell line for Group 1 (7 mice), Group 5 (7 mice), and nulliparous controls (6 mice).

1e. Harvest the left and right 3rd and 4th mammary glands and fix in formalin for histology. Task completed for MCF10ADCIS.com cell line for Group 1 (7 mice), Group 5 (7 mice), and nulliparous controls (6 mice).

1f. Harvest the liver, lung, kidney and brain tissues for determination of metastatic lesions by both IHC and PCR based techniques. Task completed for MCF10ADCIS.com cell line for Group 1 (7 mice), Group 5 (7 mice), and nulliparous controls (6 mice).

Major Updates for Task 3, Year 2:

1. Initiated H&E analysis on number of mammary glands developed within each group (currently in progress).

2. Initiated IHC analysis on myoepithelial cell markers p63, SMA, and calponin (currently in progress)

Major Updates for Tasks 1a-1f, Year 3:

1. There was no significant difference in tumor burden comparing nulliparous controls, Group 1 mice, (no lactation controls – NO LAC), and Group 5 mice (lactation group – LAC) was not increased in the pregnant group compared to their respective nulliparous (Figure 4A). There was also no significant difference in Ki67 proliferative index (Figure 4B) between tumors in the nulliparous group compared to the involution group.

2. Sequential loss of expression of p63, calponin and SMA in myoepithelial cells surrounding tumors was evident in all groups (Figure 5). Myoepithelial cells in the lactation group (LAC) surrounding DCIS lesions have a higher expression of smooth muscle actin and calponin compared to the no lactation (NO LAC) and nulliparous (CON) groups, respectively (Figure 5). Myoepithelial cell expression of p63 is lost before SMA or calponin independent of group (Figure 5).

Task 2 – Manuscript Preparation. Months 30-36

Task 2, Aim 2 Progress in First Year of Funding (1a – 1f), Year Two: Not yet initiated.

SUPPORTING DATA

FIGURES

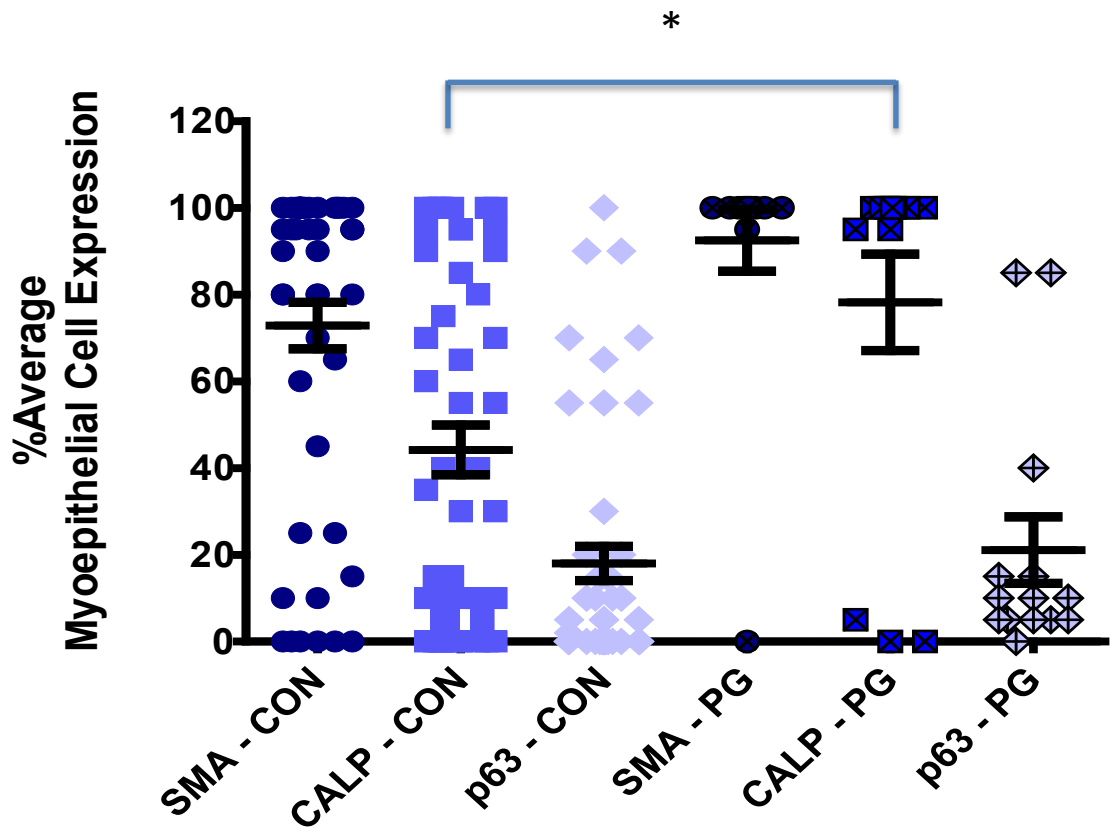


Figure 1 . Progressive myoepithelial cell layer loss during pregnancy. Quantification of the percentage of myoepithelial cell layer markers surrounding tumors from nulliparous (CON) and pregnant (PG) mouse mammary glands 4 weeks post DCIS.com injection. While expression of both SMA and calponin remain relatively high in both groups, calponin levels are significantly higher in the pregnant group compared to nulliparous controls. p63 surrounding tumors are decreased in both groups. Statistical significance was determined by one-way ANOVA and P-value justification for multiple comparisons using Tukey's approach. * $P<0.05$ Error bars = SEM.

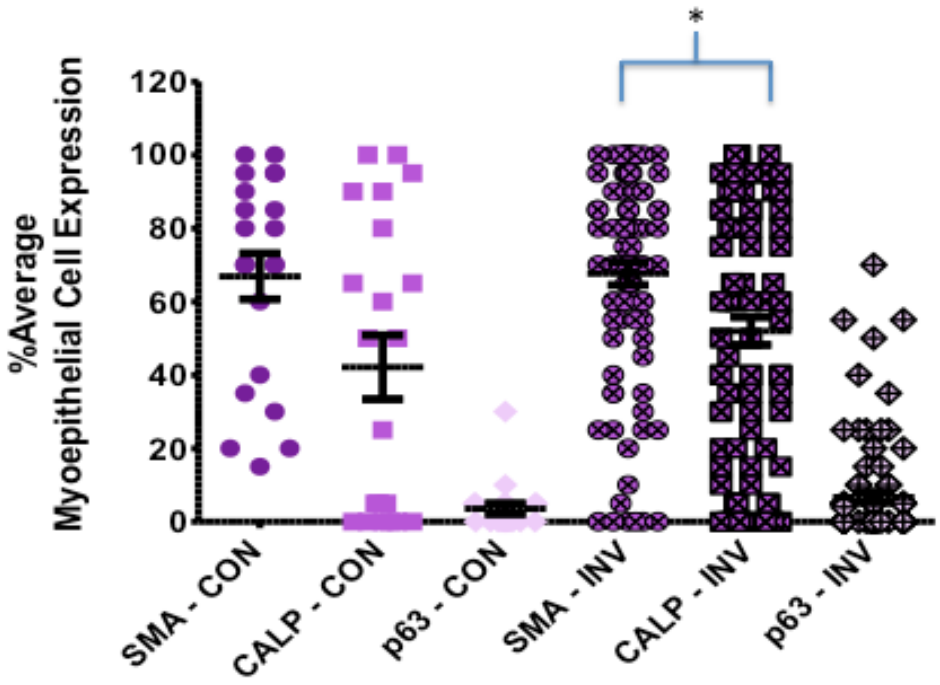
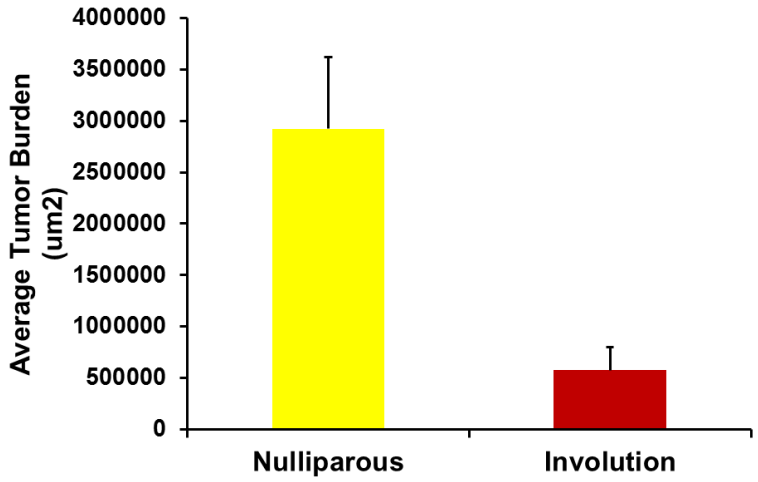


Figure 2 . Progressive myoepithelial cell layer loss during involution. Quantification of the percentage of myoepithelial cell layer markers surrounding tumors from nulliparous (CON) and post-partum involution (INV) mouse mammary glands 4 weeks post DCIS.com injection. Calponin expression is significantly lower than SMA in the involution group. Statistical significance was determined by one-way ANOVA and P-value justification for multiple comparisons using Tukey's approach. * $P<0.05$ Error bars = SEM.

3A



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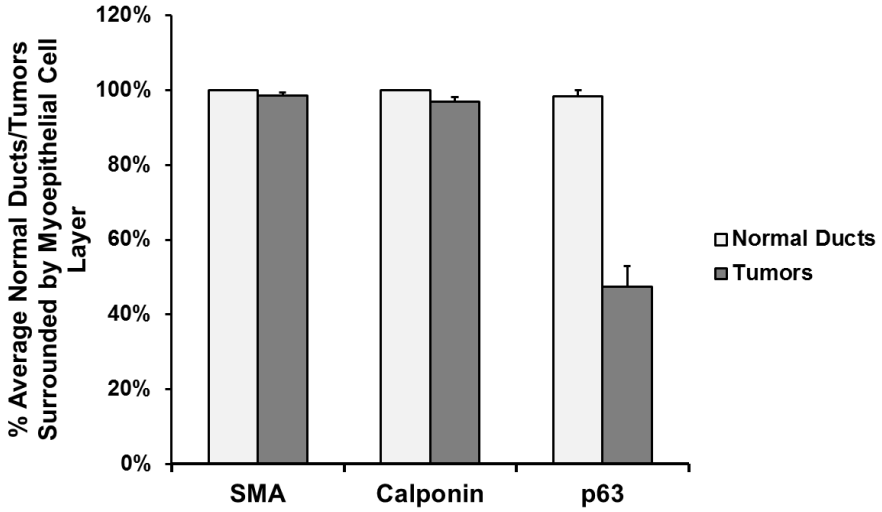
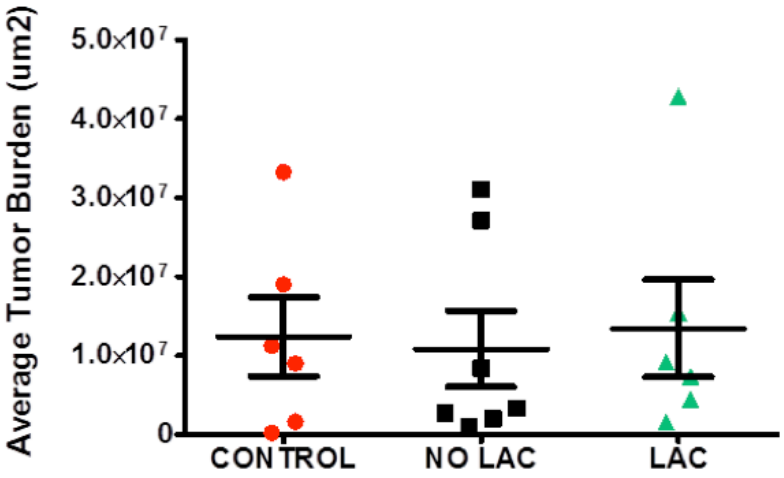


Figure 3. Assessment of tumor burden and myoepithelial cell marker coverage from HCC70 cells. (A) In contrast to the data from MCF10ADCIS.com cells, tumor burden is not increased in the involution group compared to the respective nulliparous controls. (B) Initial assessment of mammary myoepithelial cells surrounding HCC70 tumors from one nulliparous mouse. SMA and calponin remain relatively high while p63 is decreased.

4A



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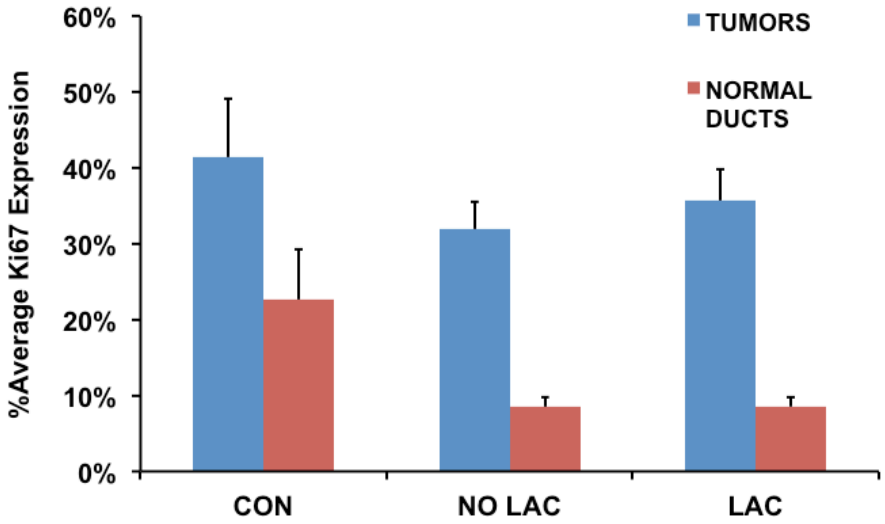


Figure 4. Effect of lactation on tumor burden and proliferation. (A) Tumor burden is not increased in the pregnant group compared to their respective nulliparous controls. (B) Ki67 proliferative index is increased in tumors from all groups compared to normal cells (p = XX). There was no significant difference in Ki67 proliferative index between tumors in the nulliparous group compared to either the no lactation group or lactation group (p = XX). Error bars = SEM. Statistical analysis = Student's paired t-test.

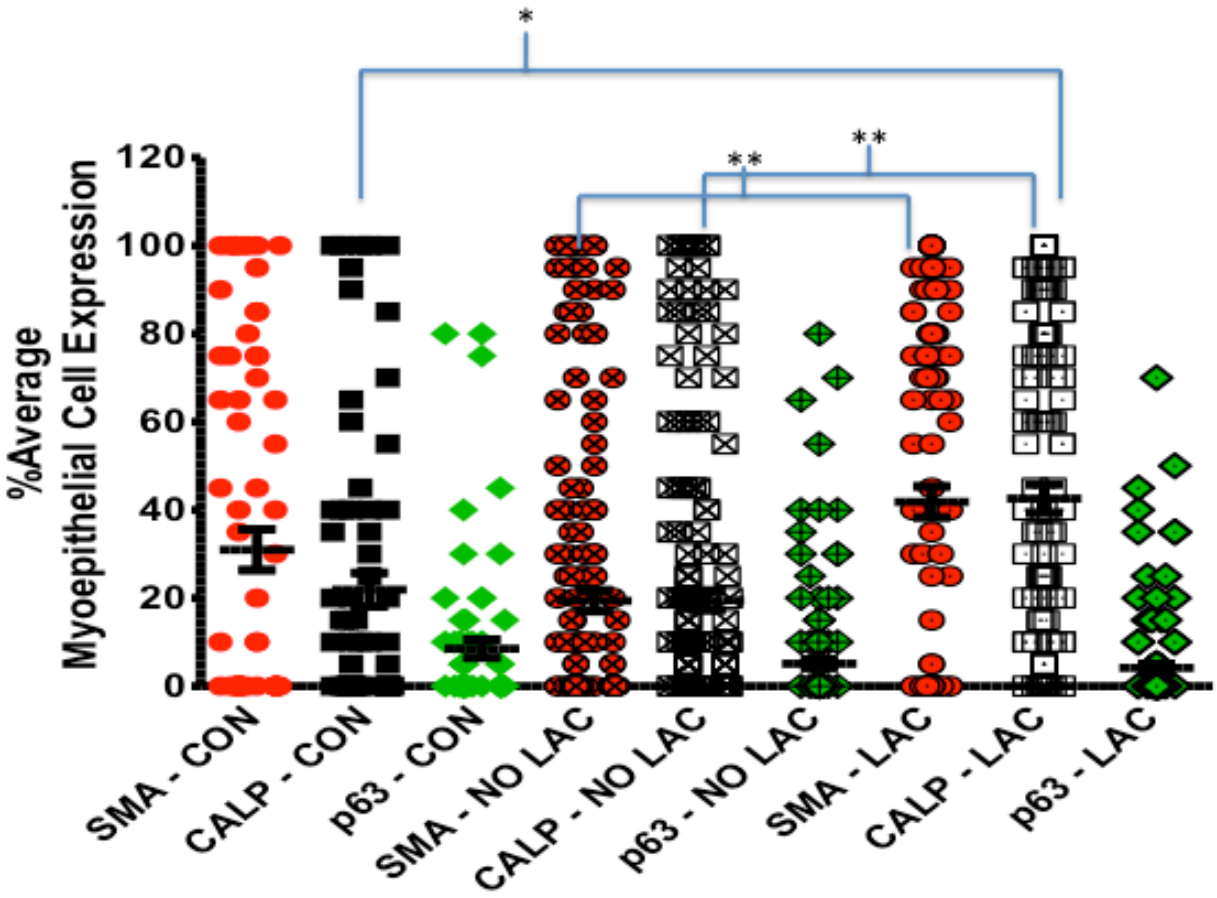


Figure 5. Quantification of the percentage of myoepithelial cell layer markers surrounding tumors in mammary glands, 8 weeks post DCIS.com injection, from nulliparous (CON), no lactation group (NO LAC), and lactation group (LAC) mice. SMA expression was significantly higher in the LAC group compared to Calponin levels in the LAC group was significantly higher than both the CON and NO LAC groups. Statistical significance was determined by one-way ANOVA and P-value justification for multiple comparisons using Tukey's approach. *P<0.05, comparing CON and LAC groups. **P<0.05, comparing NO LAC and LAC groups. Error bars = SEM.

KEY RESEARCH ACCOMPLISHMENTS

Year 1

1. Successful development of a preclinical intraductal model of human breast cancer that minimizes wound healing programs or inflammation, which allows analysis of tumor cell progression within mammary ducts in the context of environmental changes associated with normal physiology.

2. Met the criteria for a model of human breast cancer progression, as MCF10ADCIS.com cells display histologic progression from hyperplastic alveolar nodules to invasive lesions in nulliparous, pregnant and involution hosts.

3. Evaluated tumor latency, growth, burden and multifocal nature of tumor during pregnancy and involution, showing differential effects of these reproductive states on these tumor characteristics.

4. Showed that tumor burden was not increased in the pregnant group compared to nulliparous controls, but is greater in mammary glands from the involution group compared to nulliparous controls. Tumors in the pregnant group appear to be less proliferative and have slightly lower ER expression than tumors in their respective nulliparous controls, suggesting that the hormonal milieu of pregnancy may have an effect on certain mechanisms of tumor progression.

5. Initiated characterization of the protective myoepithelial cell layer as a focal point of tumor progression. p63 positivity appears to be lost first in all tested microenvironments and calponin positivity appears to lost preferentially in the post-partum involution environment. These data may reflect key differences in the influence of these reproductive states on tumor progression.

Year 2

1. We demonstrate proof-of-principal that host physiology (i.e. pregnancy and postpartum involution) can influence DCIS progression, identifying this model as relevant for addressing key questions such as influence of host reproductive status on breast cancer progression.

2. Our model permits a rigorous evaluation of the effects of DCIS progression on molecular changes in the myoepithelium, which serves as a barrier to invasive cancer. Our data suggests that this protective layer is more compromised during post-partum involution than during pregnancy and nulliparity.
   In both environments SMA positivity remains relatively stable, suggesting that the actin biostructure may be a later barrier broken in tumor progression. p63 positivity appears to be lost first in all tested microenvironments and calponin positivity appears to lost preferentially in the post-partum involution environment. These data may reflect key differences in the influence of these reproductive states on tumor progression.

3. Our data suggests that the myoepithelial cell layer around tumors may not be compromised during pregnancy, suggesting that pregnancy may maintain the myoepithelial cell layer and thus a more tumor suppressive environment.

Years 1-3

1. Our intraductal model of human breast cancer provides a rigorous approach to studying tumor progression from early stage intraductal hyperplasia to invasion. This model is particularly suited to studying host effects on DCIS progression. Since occult tumors in women develop within ducts, we propose that this teat injection model will facilitate research of early disease progression, a requisite for research focused on breast cancer prevention and inhibition of local invasion.

2. With respect to nulliparous controls, tumor burden is not increased in the pregnant group, or when tumors are exposed to lactation, but is greater in mammary glands from the involution group. Our group has recently suggested that postpartum breast cancer be divided in two groups: cases diagnosed during pregnancy that have a better prognosis and cases diagnosed during the post-partum period which have a poorer prognosis [7]. Importantly, our preclinical data model the human epidemiological data on postpartum breast cancer [8].

3. Our intraductal model also permits a rigorous evaluation of early molecular changes within the mammary myoepithelium, which serves as a barrier to invasive cancer. Our data, demonstrating that DCIS lesions with an intact myoepithelial cell layer display progressive loss of specific myoepithelial cell markers, suggest that the myoepithelium is compromised prior to DCIS progression to invasive disease. Our data further suggests that this protective layer may be maintained by tumors formed within the pregnancy-lactation cycle. p63 expression appears to be lost first in all tested microenvironments, but calponin is significantly higher in myoepithelial cells surrounding tumors from both the pregnant and lactation group. These data may reflect key differences in the influence of these reproductive states on tumor progression.

REPORTABLE OUTCOMES

Manuscripts:

1. **Tanya D. Russell**, Samiat Agunbiade, Sonali Jindal, Dexiang Gao, Virginia Borges, and Pepper Schedin. Evidence for progressive loss of myoepithelial cell markers with DCIS progression to invasive disease. Resubmission in progress.

1. **Tanya D. Russell** and Pepper Schedin. A Novel Intraductal Delivery Model that Permits Study of Host Physiology on Human Ductal Carcinoma In Situ Progression. Submitted.

Abstracts:

1. Pepper Schedin, Eryn Callihan, Traci Lyons, **Tanya Russell**, Holly Martinson and Virginia Borges. Host reproductive heterogeneity determines prognosis of young women's breast cancer. Princess Takamatsu Symposium, Tokyo, Japan, November 2012.

2. **Tanya D. Russell,** Samiat Agunbiade, Sonali Jindal, Jaime Fornetti, Pepper Schedin, and Virginia Borges. A Novel Mammary Intraductal Delivery Model that Permits Study of Human Ductal Carcinoma In Situ Progression. October 27-30, 2012 Fifth AACR Conference on the "Science of Cancer Health Disparities in Racial/Ethnic Minorities and the Medically Underserved", San Diego, California.

3. Pepper Schedin, Traci R. Lyons, **Tanya Russell**, Holly Martinson, Sonali Jindal, Eryn Callihan, and Virginia Borges. COX-2 inhibitors target multiple pro-tumorigenic pathways involved in metastasis of postpartum breast cancers. 11th Annual AACR International Frontiers in Cancer Prevention Research Conference, Anaheim, California, October 16-19, 2012.

4. **Tanya D. Russell,** Samiat Agunbiade, Sonali Jindal, Jaime Fornetti, Pepper Schedin, and Virginia Borges. A Novel Mammary Intraductal Delivery Model that Permits Study of Human Ductal Carcinoma In Situ Progression. September 2012 UCD Center for Women's Health Research's Women's Health Research Day, Aurora, Colorado.

1. Pepper Schedin, Traci Lyons, Jenean O'Brien, Eryn Callahan, **Tanya Russell**, Holly Martinson, and Virginia Borges. Mammary gland involution drives breast cancer progression through collagen and COX-2. IABCR Breakthrough Conference, April 15-18, 2012.

2. **Tanya D. Russell,** Jaime Fornetti, and Pepper Schedin**.** Does Pregnancy and Post-Partum Involution Promote Tumorigenesis in a Preclinical Model for Early Stage Human Breast Cancer? Department of Defense Era of Hope Conference, Orlando, Florida, August 2-5, 2011.

3. Pepper Schedin, Traci R. Lyons, Jenean O'Brien, **Tanya Russell**, Holly Martinson, Patricia J. Keely, and Virginia Borges. Postpartum mammary gland involution promotes breast tumor progression through collagen and COX-2 and is inhibited by NSAIDS. Department of Defense Era of Hope Conference, August 2-5, 2011.

4. V.F. Borges, T. Lyons, J. O'Brien, **T. Russell**, H. Martinson, P. Keely, P.J. Schedin. The Role of Collagen and COX-2 in post-partum breast involution on the progression of pregnancy-associated breast cancer and its inhibition by NSAIDs. ASCO Annual Meeting, June 3-7, 2011.

5. **Tanya D. Russell**, Sonali Jindal, Jaime Fornetti, and Pepper Schedin. A Preclinical Mammary Intraductal Model to Study Early Stage Human Breast Cancer. 102nd AACR Annual Meeting "Innovation and Collaboration: The Path to Progress", Orlando, Florida, April 2-6, 2011.

6. **Tanya D. Russell,** Sonali Jindal, Jaime Fornetti, and Pepper Schedin. Does Pregnancy and Post-Partum Involution Promote Tumorigenesis in a Preclinical Model for Early Stage Human Breast Cancer? University of Colorado Denver Mammary Gland Biology Retreat, Aurora, CO, January 20-21, 2011.

7. **Tanya D. Russell**, Jaime Fornetti, and Pepper Schedin. Pregnancy and Postpartum Involution Promote Tumorigenesis in a Preclinical Model for Triple Negative/Basal Breast Cancer. Third AACR Conference on "The Science of Cancer Health Disparities in Racial/Ethnic Minorities and the Medically Underserved", Miami, FL, September 30-October 3, 2010.

Oral Presentations:
None (Year 3)

1. **Tanya D. Russell.** Effect of Pregnancy and Partum Involution on DCIS Progression. March 1, 2012, Research in Progress, Division of Medical Oncology, University of Colorado Denver.

2. **Tanya D. Russell.** Effect of Pregnancy and Partum Involution on DCIS Progression. March 6, 2012, Postdoctoral Seminar Series, University of Colorado Denver.

3. **Tanya D. Russell.** Pregnancy and Involution Promote Tumorigenesis in a Preclinical Model for Early Stage Human Breast Cancer. January 2011 Research in Progress, Division of Medical Oncology, University of Colorado Denver.

4. **Tanya D. Russell.** Does Pregnancy and Post-Partum Involution Promote Tumorigenesis in a Preclinical Model for Early Stage Human Breast Cancer? January 2011 University of Colorado Denver Mammary Gland Biology Retreat, Aurora, Colorado.

5. **Tanya D. Russell.** Department of Health and Human Services (HHS) National Institutes of Health (NIH) National Cancer Institute (NCI) 2010 Cancer Research Imaging Camp June 20–25, 2010 St. Louis, MO.

Poster Presentations:

1. **Tanya D. Russell,** Samiat Agunbiade, Sonali Jindal, Jaime Fornetti, Pepper Schedin, and Virginia Borges. A Novel Mammary Intraductal Delivery Model that Permits Study of Human Ductal Carcinoma In Situ Progression. October 27-30, 2012 Fifth AACR Conference on the "Science of Cancer Health Disparities in Racial/Ethnic Minorities and the Medically Underserved", San Diego, California.

2. **Tanya D. Russell,** Samiat Agunbiade, Sonali Jindal, Jaime Fornetti, Pepper Schedin, and Virginia Borges. A Novel Mammary Intraductal Delivery Model that Permits Study of Human Ductal Carcinoma In Situ Progression. September 2012 UCD Center for Women's Health Research's Women's Health Research Day, Aurora, Colorado.

3. **Tanya D. Russell,** Jaime Fornetti, and Pepper Schedin**.** Does Pregnancy and Post-Partum Involution Promote Tumorigenesis in a Preclinical Model for Early Stage Human Breast Cancer? October 2011 Cancer Biology Poster Session, Aurora, Colorado.

4. **Tanya D. Russell,** Jaime Fornetti, and Pepper Schedin**.** Does Pregnancy and Post-Partum Involution Promote Tumorigenesis in a Preclinical Model for Early Stage Human Breast Cancer? August 2011 Department of Defense Era of Hope Conference, Orlando World Marriot Center, Orlando, Florida.

5. **Tanya D. Russell,** Jaime Fornetti, and Pepper Schedin**.** Does Pregnancy and Post-Partum Involution Promote Tumorigenesis in a Preclinical Model for Early Stage Human Breast Cancer? June 2011 Gordon Research Conference on Mammary Gland Biology, Salve Regina University, Newport, Rhode Island.

6. **Tanya D. Russell**, Sonali Jindal, Jaime Fornetti, and Pepper Schedin. A Preclinical Mammary Intraductal Model to Study Early Stage Human Breast Cancer. April 2011 102nd AACR Annual Meeting "Innovation and Collaboration: The Path to Progress", Orlando, Florida.

7. **Tanya D. Russell**, Jaime Fornetti, and Pepper Schedin. Pregnancy and Postpartum Involution Promote Tumorigenesis in a Preclinical Model for Triple Negative/Basal Breast Cancer. 2010 UCD Third Annual Women's Health Research Day, Aurora, Colorado.

8. **Tanya D. Russell**, Jaime Fornetti, and Pepper Schedin. Pregnancy and Postpartum Involution Promote Tumorigenesis in a Preclinical Model for Triple Negative/Basal Breast Cancer. 2010 Third AACR Conference on the "Science of Cancer Health Disparities in Racial/Ethnic Minorities and the Medically Underserved", Miami, Florida.

Awards:

1. FLARE (Future Leaders Advancing Research in Endocrinology) Workshop Award Winner, the Endocrine Society, January 25-26, 2013.

2. AACR Minority Scholar in Cancer Research Award - Third AACR Conference on the "Science of Cancer Health Disparities in Racial/Ethnic Minorities and the Medically Underserved", October 27-30, 2012.

3. Poster Award – UCD Center for Women's Health Research's Women's Health Research Day, Aurora, CO, September 2012.

None (Year 2)

AACR Minority Scholar in Cancer Research Award - Third AACR Conference on the "Science of Cancer Health Disparities in Racial/Ethnic Minorities and the Medically Underserved", 2010

Patents and licenses: none

Development of cell lines, tissue, serum repositories: none

Informatics: none

Funding applied for based on this work: none

Personnel receiving pay from research effort: none

Employment or research opportunities:

1. Medical Writer Intern, Aegis Creative Communications, Lakewood, CO September 11, 2013- present.

2. "Grant Writing 101", University of Colorado Anschutz Medical Campus Assistive Technology Partners, Denver, CO, May 13-15, 2013.

3. "Translational Research: From Cell Lines to Animals to People", University of Colorado Denver Anschutz Medical Campus Learning Center, Aurora, CO, December 4, 2012.

1. University of Colorado Anschutz Medical Campus workshop, "Career Planning in the Context of Life Planning", May 4, 2011, Aurora, CO.

2. **Tanya D. Russell.** Department of Health and Human Services (HHS) National Institutes of Health (NIH) National Cancer Institute (NCI) 2010 Cancer Research Imaging Camp June 20–25, 2010 St. Louis, MO.

CONCLUSION

Our murine intraductal model of human breast cancer provides a rigorous approach to the study of early-stage breast cancer progression and demonstrates the ability to assess changes in the myoepithelium as well as the influence of the host reproductive state on DCIS progression. Understanding the role of the myoepithelial cell layer in early stage cancer may provide insight in the prevention of early invasion, and ultimately metastasis. Twenty percent of new cancers diagnosed are DCIS, and standard treatment typically involves surgery and radiation. A better understanding of the role of the myoepithelium in early stage cancers may help prevent unnecessary treatments [9] Additionally, these initial studies begin to help address the question of why breast cancer, when diagnosed within close proximity to a recent pregnancy, is more aggressive and more likely to spread and provide novel insight into the especially poor prognosis of young African American women.

REFERENCES

1. **Millikan, R.C., et al., *Epidemiology of basal-like breast cancer.* Breast Cancer Res Treat, 2008. 109(1): p. 123-39.**
2. **Palmer, J.R., et al., *Parity and lactation in relation to estrogen receptor negative breast cancer in African American women.* Cancer Epidemiol Biomarkers Prev, 2011. 20(9): p. 1883-91.**

3. **Lyons, T.R., et al., *Postpartum mammary gland involution drives progression of ductal carcinoma in situ through collagen and COX-2.* Nat Med, 2011. 17(9): p. 1109-15.**
4. **Russell, T.D., et al., *Transduction of the mammary epithelium with adenovirus vectors in vivo.* J Virol, 2003. 77(10): p. 5801-9.**
5. **Nguyen, D.-A.D., et al., *Intraductal injection into the mouse mammary gland.*, in *Methods in Mammary Gland Biology and Breast Cancer Research*, M.M. Ip and B.B. Asch, Editors. 2000, Kluwer Academic/Plenum: N.Y. p. 259-270.**
6. **Neve, R.M., et al., *A collection of breast cancer cell lines for the study of functionally distinct cancer subtypes.* Cancer Cell, 2006. 10(6): p. 515-27.**
7. **Lyons, T.R., P.J. Schedin, and V.F. Borges, *Pregnancy and breast cancer: when they collide.* J Mammary Gland Biol Neoplasia, 2009. 14(2): p. 87-98.**
8. **Callihan, E.B., et al., *Postpartum diagnosis demonstrates a high risk for metastasis and merits an expanded definition of pregnancy-associated breast cancer.* Breast Cancer Res Treat, 2013. 138(2): p. 549-59.**
9. **Schnitt, S.J., et al., *Ductal carcinoma in situ (intraductal carcinoma) of the breast.* N Engl J Med, 1988. 318(14): p. 898-903.**

APPENDICES: Supporting Data from Years 1 and 2, Manuscripts, Abstracts,

SUPPORTING DATA

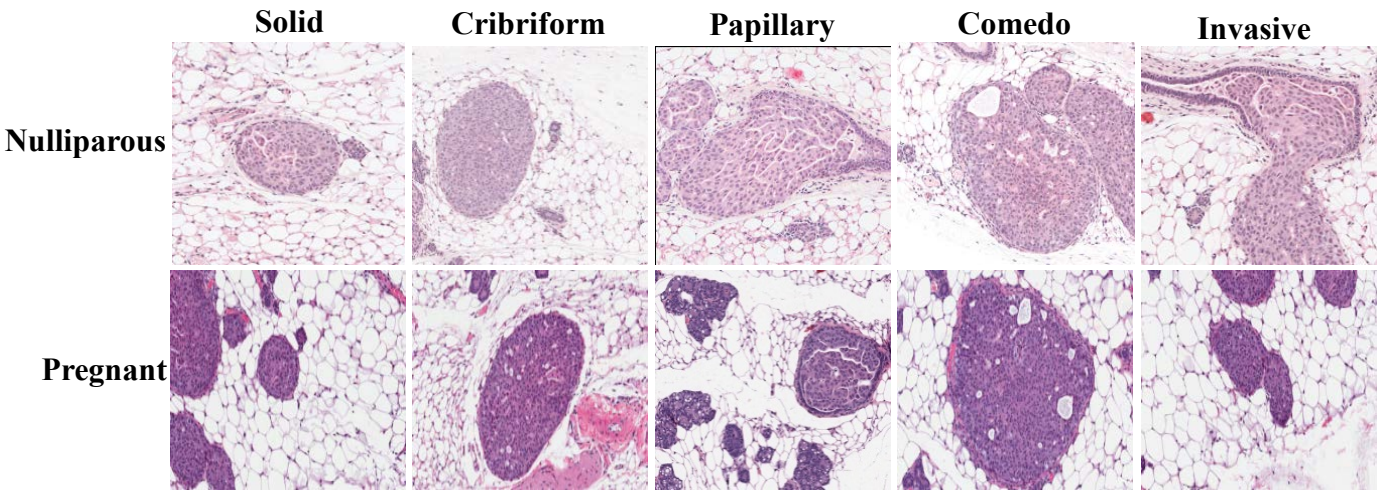


Figure 1. Hemotoxylin and eosin staining of mouse mammary glands intraductally injected with MCF10ADCIS.com tumor cells. MCFDCIS10A.com cells undergo stages of tumor development (solid, cribriform, papillary, comedo, and locally invasive) in nulliparous, (top panels) and pregnant (bottom panels) environments. Scale bar = 50 um.

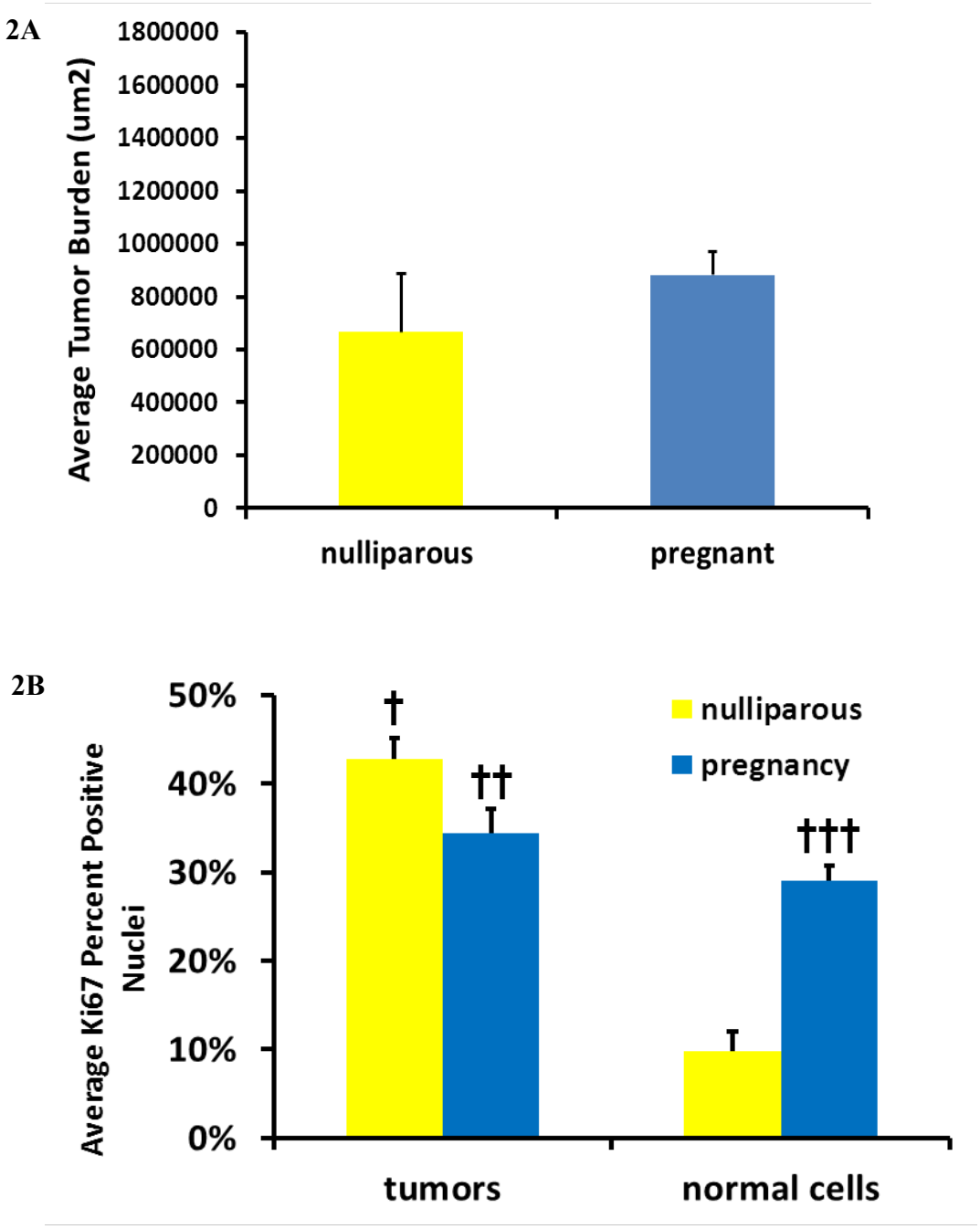
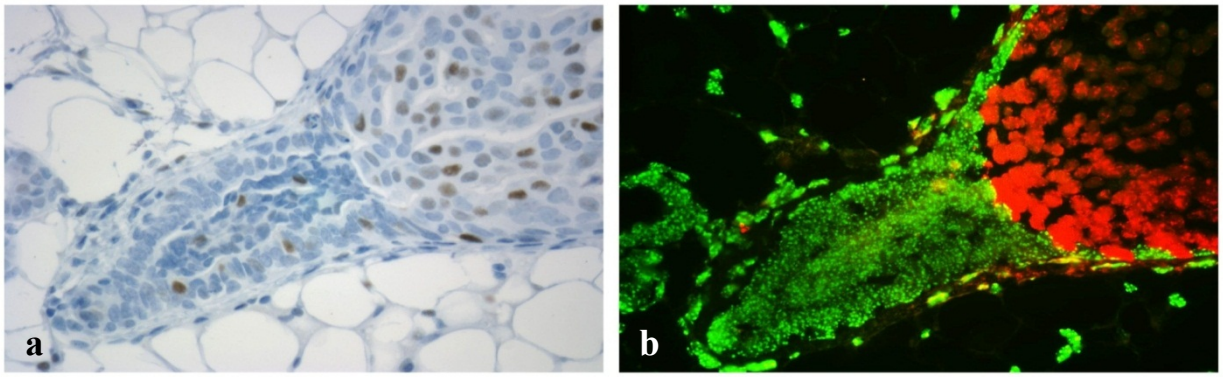


Figure 2. Effect of pregnancy on tumor burden and proliferation. (A) Tumor burden is not increased in the pregnant group compared to their respective nulliparous controls. (B) Ki67 proliferative index is increased in tumors from the nulliparous group compared to normal cells ($^{\dagger}p = 1.956E-06$). Interestingly, there was no difference in Ki67 proliferative index between tumors and normal cells in the pregnant group ($p = 0.1256$). There was a slight but significant decrease in Ki67 proliferative index in tumors from the pregnant group compared to tumors from their respective nulliparous controls ($^{\dagger\dagger}p = 0.0441$). As expected, Ki67 proliferative index was much higher in normal cells from the pregnant group compared to nulliparous controls ($^{\dagger\dagger\dagger}p = 1.407E-05$). Error bars = SEM. Statistical analysis = Student's paired t-test.

3A



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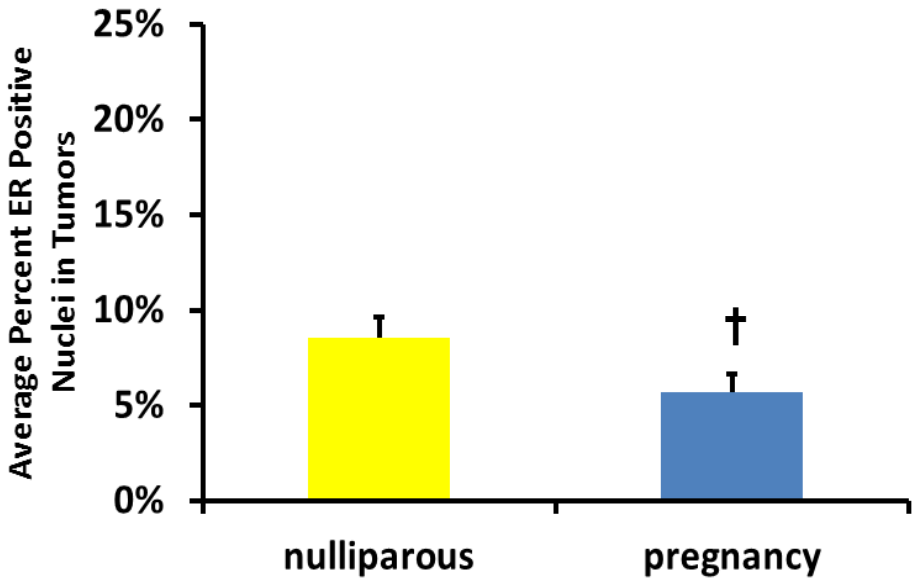


Figure 3. Effect of pregnancy on ER re-expression. (A) IHC analysis of ER (a, brown) shows ER expressed in some, but not all, MCF10ADCIS.com tumor cells. These data were confirmed by FISH analysis (b) of human (red) and mouse (green) COT-1 DNA. (B) ER expression in MCF10ADCIS.com cells is slightly lower in the pregnant group compared to their respective nulliparous group (*p = 0.0697). Error bars = SEM. Statistical analysis = Student's paired t-test.

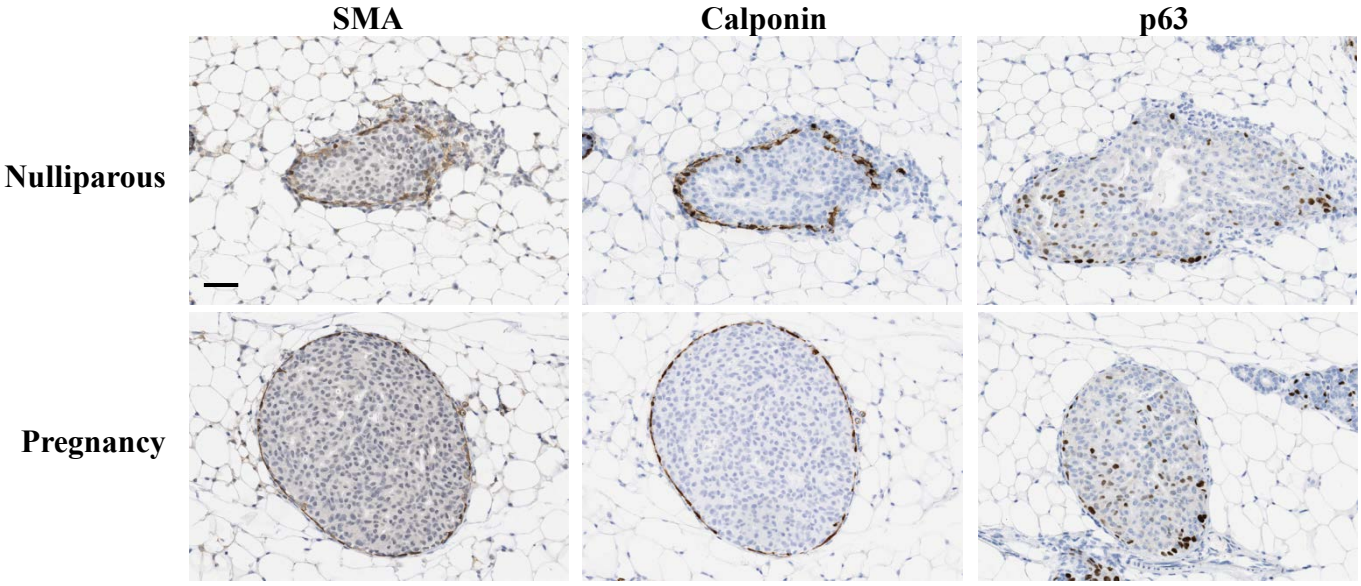
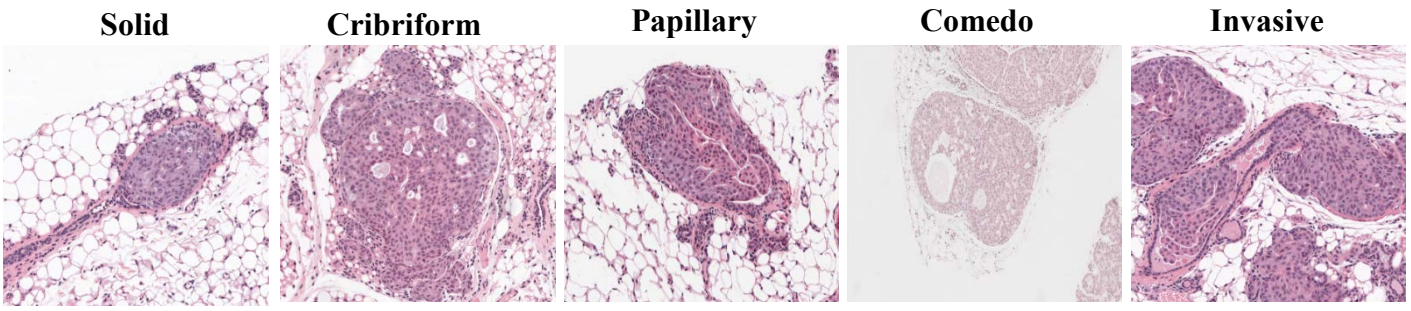


Figure 4. Myoepithelial cell layer markers outline normal ductal structures and tumors. Serial IHC analysis of myoepithelial cell markers smooth muscle actin (SMA; brown, left), calponin (brown, middle) and p63 (brown, right) outlining tumors in the nulliparous and pregnant host environments. Images scanned using Aperio software. Scale bars = 50 μm.

Table 1. Quantification of tumors surrounded by myopepithelial cell markers in nulliparous and pregnant host environments.

GROUP	>50% Tumors Surrounded by SMA	>50% Tumors Surrounded by Calponin	>50% Tumors Surrounded by p63
Nulliparous	60%	52%	40%
Pregnancy	92%	71%	46%

5A



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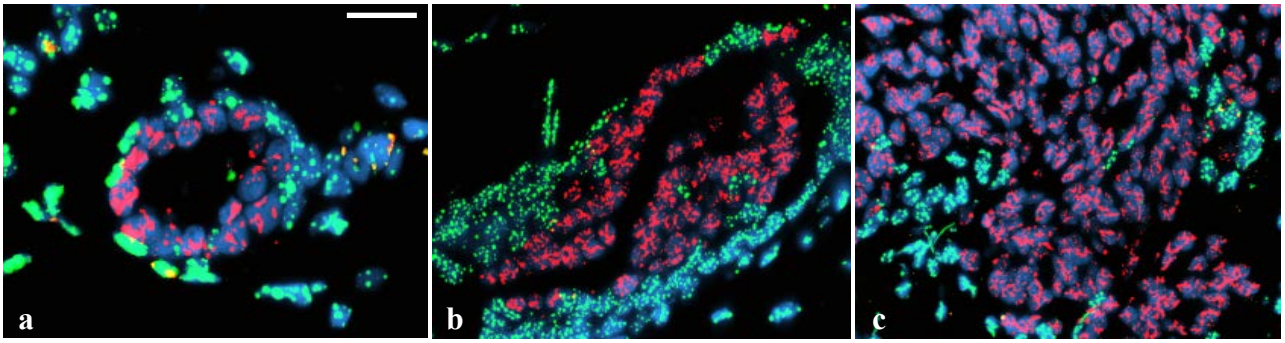
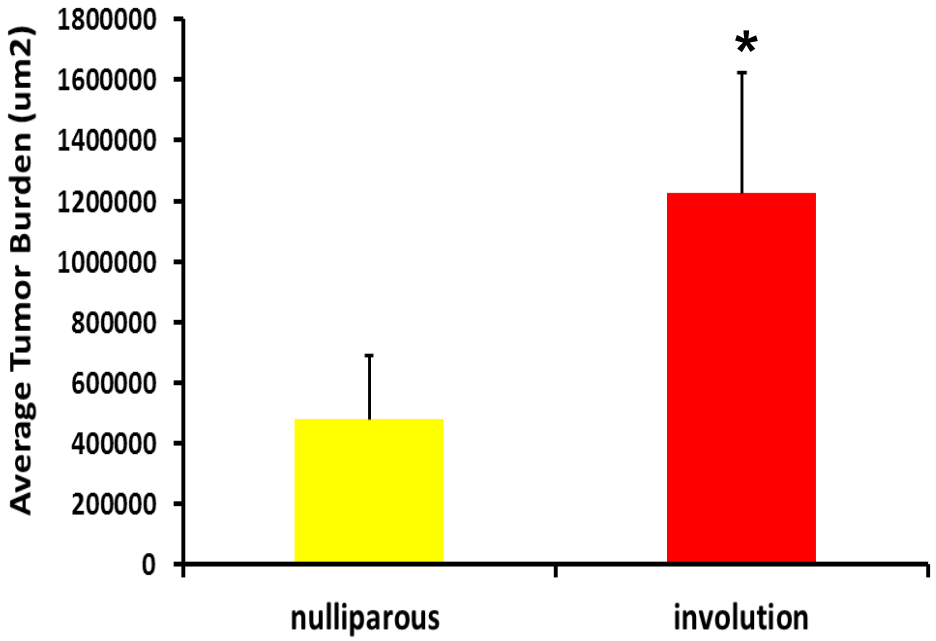


Figure 5. DCIS characteristics of MCF10ADCIS.com cells in the involution host environment. (A) MCFDCIS10A.com cells undergo stages of tumor development (solid, cribriform, papillary, comedo, and locally invasive) in the involution host environment. Similar DCIS characteristics are present in the nulliparous group (see Figure 1). (B) Fluorescent in situ Hybridization (FISH) detection of human and mouse cells in intraductal model. FISH analysis for COT-1 DNA (red = human COT-1; green = mouse COT-1) reveals evidence of tumor progression from (A) hyperplastic alveolar nodules (B) to ductal carcinoma situ to (C) local invasion. Scale bar = 40 μm.

6A



6B

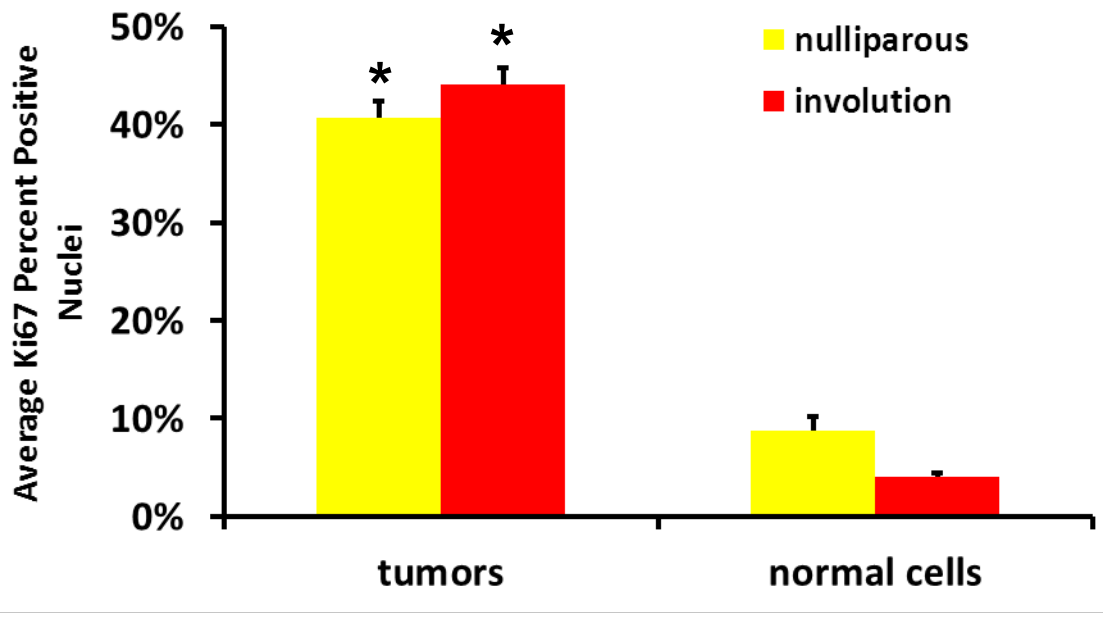


Figure 6. Effect of involution on tumor burden and proliferation. (A) Tumor burden is greater in the involution group compared to their respective nulliparous controls (*p = .0637). (B) Ki67 proliferative index is increased in tumors from both the nulliparous and involution groups compared to normal cells (*p = 5.859E-08 and 1.082E-07, respectively). There was no significant difference in Ki67 proliferative index between tumors in the nulliparous group compared to the involution group (p = 0.1737). However, there was a decrease in Ki67 proliferative index in normal cells from the involution group compared to normal cells from their respective nulliparous controls (**p = 0.021). Error bars = SEM. Statistical analysis = Student's paired t-test.

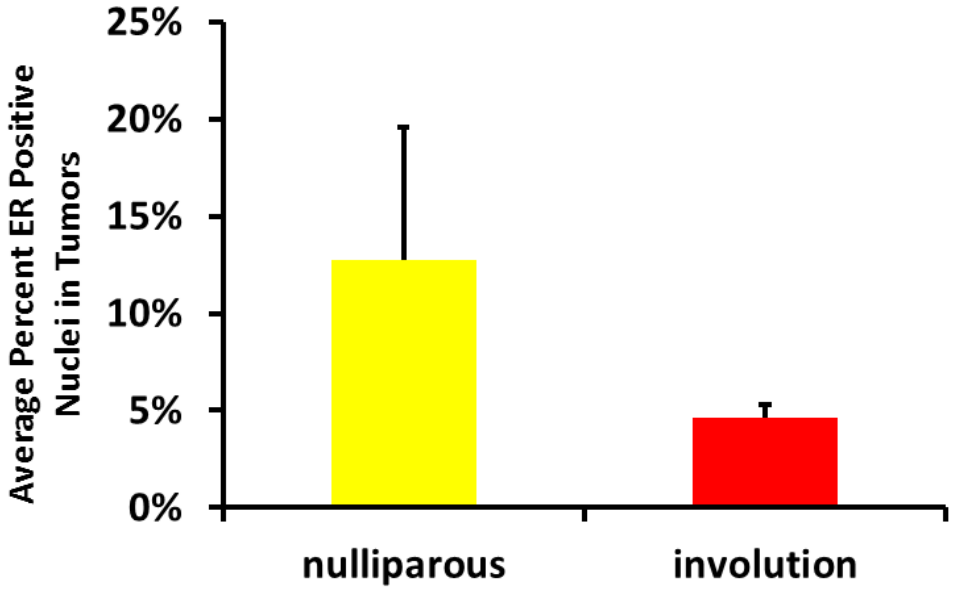


Figure 7. Effect of involution on ER re-expression. There was no difference in ER expression in tumors from the involution group compared to their respective nulliparous controls (*p = 0.3009). Error bars = SEM. Statistical analysis = Student's paired t-test.

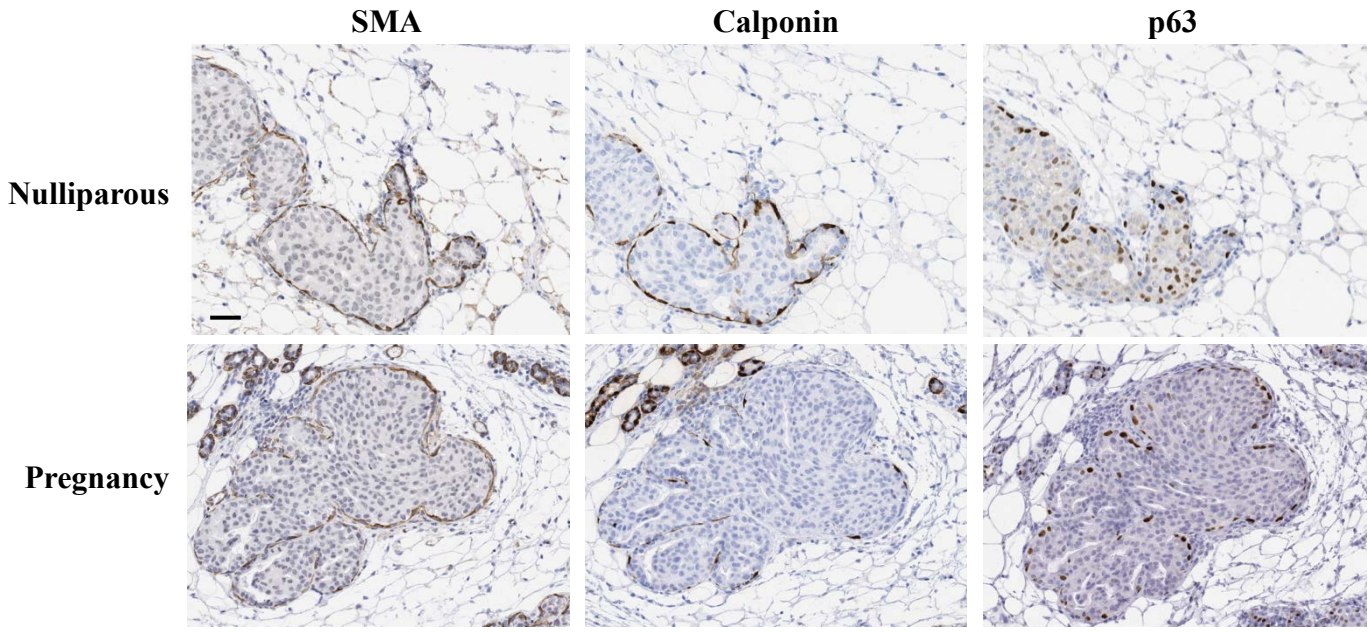


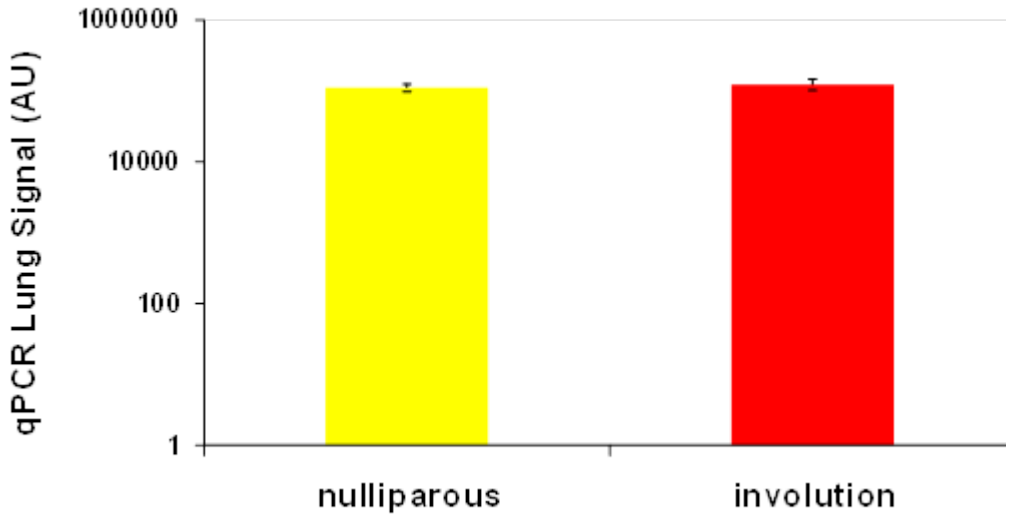
Figure 8. Myoepithelial cell layer markers outline normal ductal structures and tumors. Serial IHC analysis of myoepithelial cell markers smooth muscle actin (SMA; brown, left), calponin (brown, middle) and p63 (brown, right) outlining tumors in the nulliparous and involution host environments. Images scanned using Aperio software. Scale bars = 50 μm.

Table 2. Quantification of tumors surrounded by myopepithelial cell markers in nulliparous and pregnant host environments.

GROUP	>50% Tumors Surrounded by SMA	>50% Tumors Surrounded by Calponin	>50% Tumors Surrounded by p63
Nulliparous	88%	35%	24%
Involution	88%	40%	43%

GROUP	% Tumors Surrounded by More p63 than Calponin	% Tumors Surrounded by Less p63 than Calponin	% Tumors Surrounded by the Same Amount of p63 than Calponin
Involution	53%	30%	15%

9A



9B

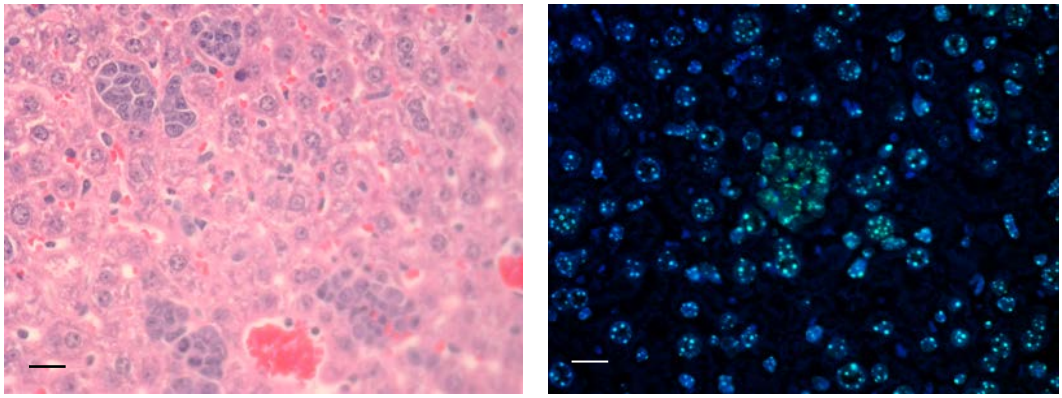
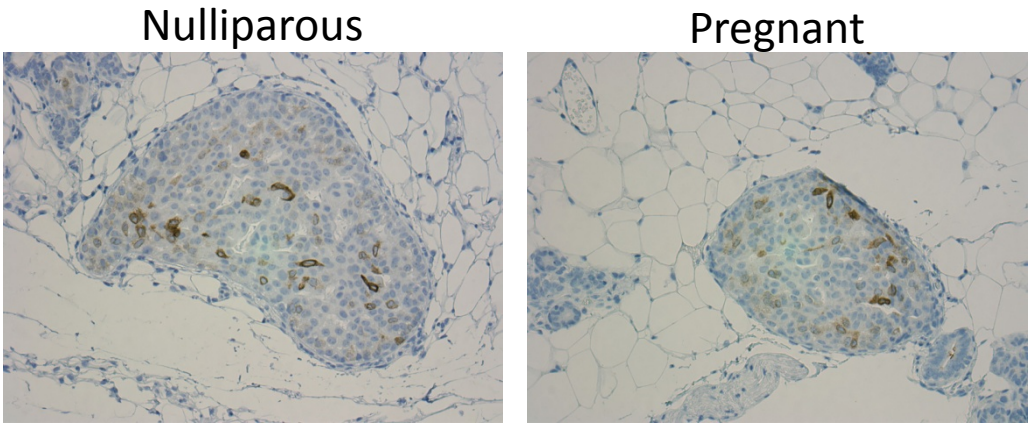


Figure 9. No evidence of lung or liver metastasis in the nulliparous and involution host microenvironments. (A) qRT-PCR analysis of lung for human β2M transcripts in arbitrary units (a.u.) after normalizing to actin. No metastasis was detected in either the nulliparous (n=6) group or the involution (n=5) group ($p = 0.642$). Error bars = SEM. Statistical analysis = unpaired t test. (B) Hemotoxylin and eosin showed suspected areas of liver metastasis (panel a, arrows), but FISH analysis for COT-1 DNA (red = human COT-1; green = mouse COT-1) confirmed no metastatic lesions (panel b, arrows). Magnification = 40X. Scale bars = 20 um.

SUPPORTING DATA

FIGURES

1A



1B

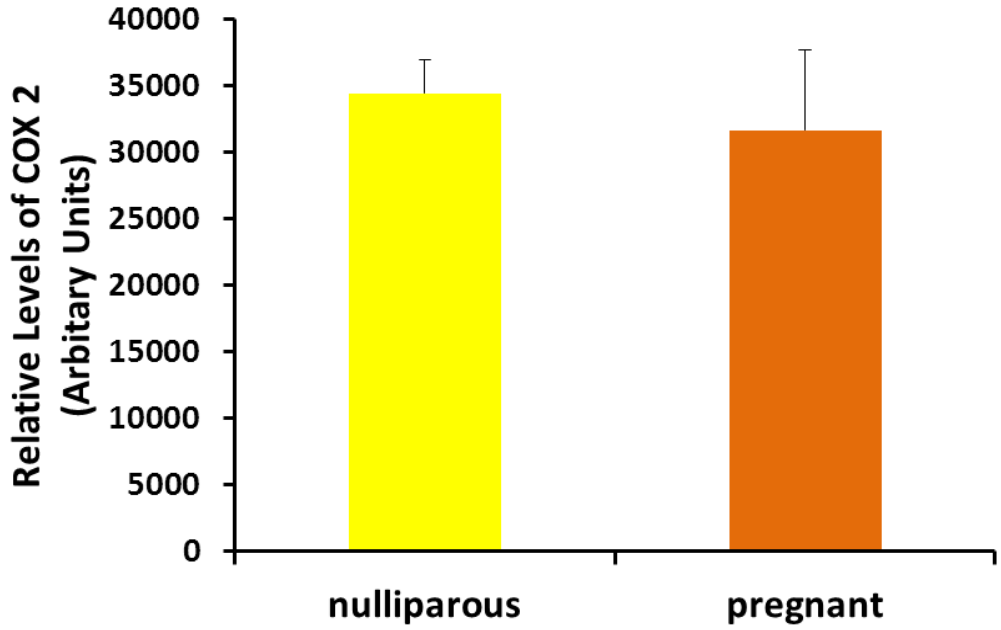
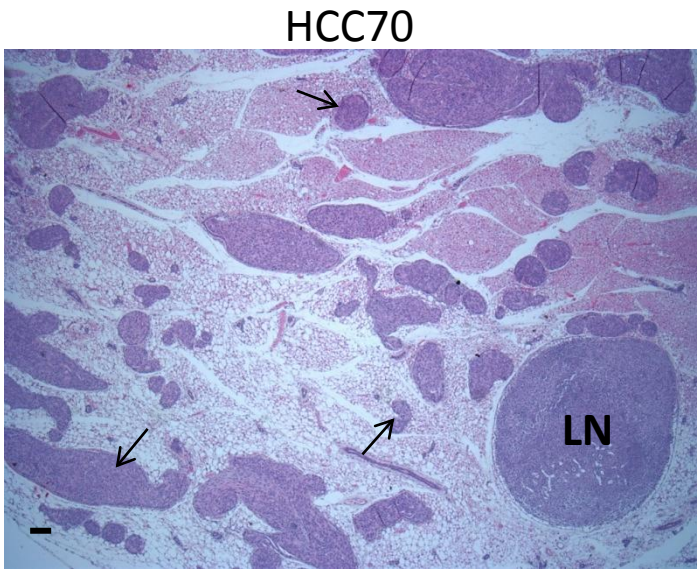


Figure 1. Effect of pregnancy on COX2 expression. (1A) IHC analysis shows COX2 (brown) expression in MCF10ADCIS.com tumors in nulliparous (left panel) and pregnant (right panel) mouse mammary glands. (1B) COX2 expression in MCF10ADCIS.com cells in the pregnant group and their respective nulliparous group are similar. Error bars = SEM.

2A



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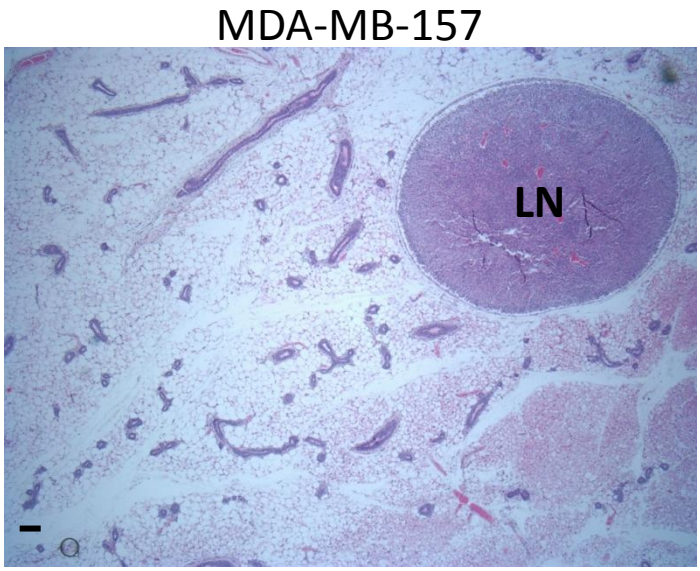


Figure 2. Hemotoxylin and eosin staining of mouse mammary glands intraductally injected with MDA-MB-157 or HCC70 tumor cells. Mouse mammary glands were harvested 4 weeks post intraductal injection. (2A) Robust tumor formation was seen in mammary glands injected with HCC70 cells (arrows). (2B) No tumors were evident in mammary glands injected with MDA-MB-157 cells. LN = lymph node. Scale bars = 50 um. Magnification = 2.5X.

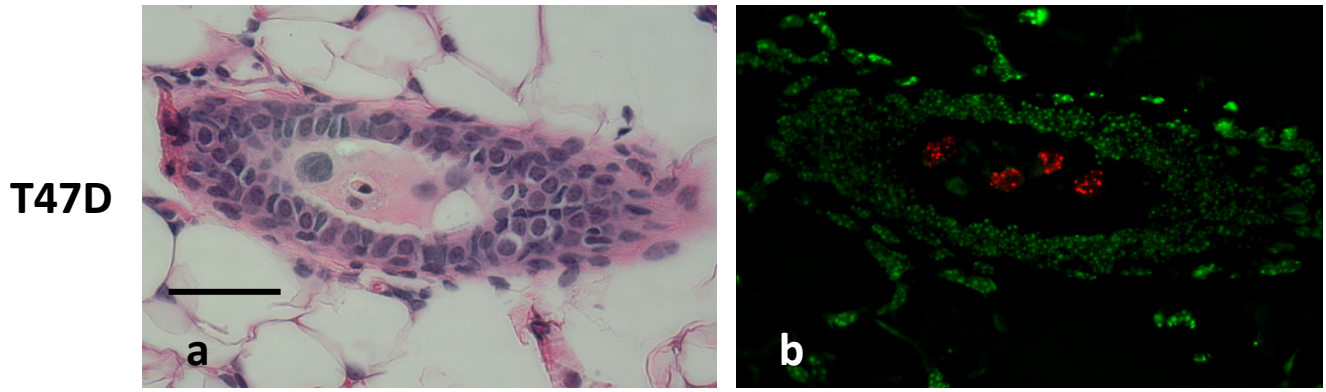
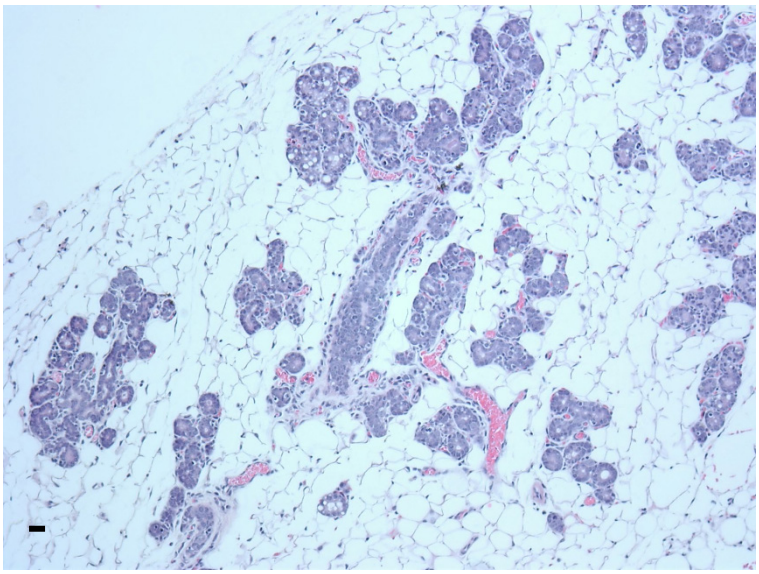


Figure 3. Hemotoxylin and eosin (H&E) staining and fluorescence in situ hybridization (FISH) analysis of nulliparous mouse mammary glands intraductally injected with a luminal A (T47D) breast cancer cell line. At 4 weeks post mammary intraductal injection in the absence of estrogen supplementation, T47D cells did not form tumors (a). FISH analysis for COT-1 DNA (red = human COT-1; green = mouse COT-1) confirms the presence of T47D cells within mammary ducts using FISH analysis (b). Scale bar = 50 um. Magnification = 40X.

4A



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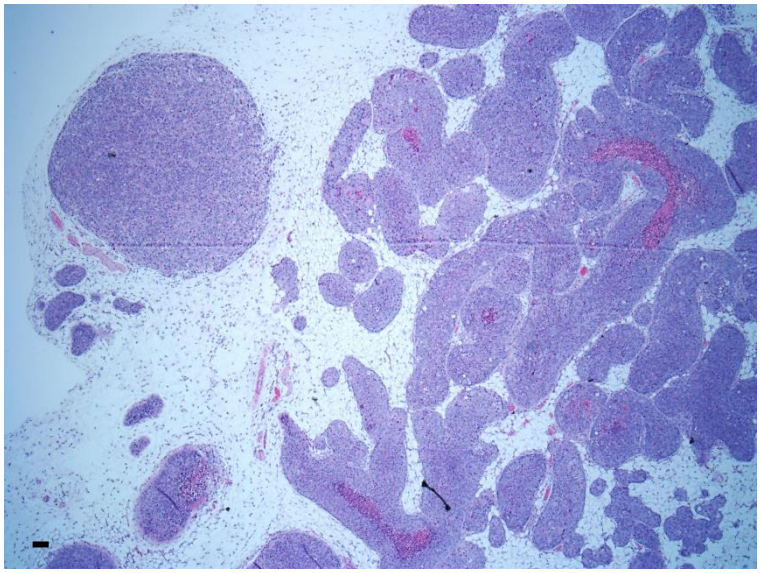
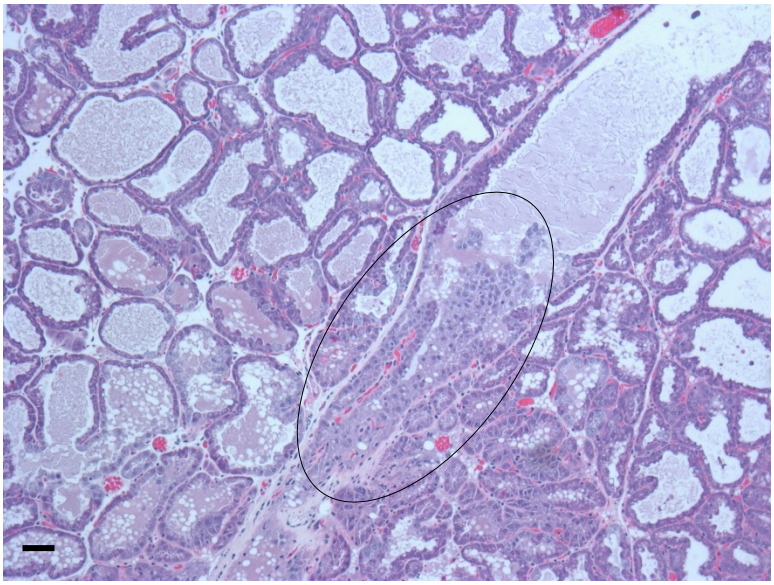


Figure 4. H&E staining of nulliparous mouse mammary glands intraductally injected with T47D and MCF7 breast cancer cell lines in the presence of estrogen supplementation. Mice were supplemented with an 0.72 mg estrogen pellet at time of intraductal injection. (4A) While estrogen supplementation stimulated a pregnant phenotype in the mammary glands, no T47D tumors were evident. (4B) MCF7 had a robust response to estrogen supplementation and formed tumors. Scale bars = 50 um. Magnification = 10X.

5A



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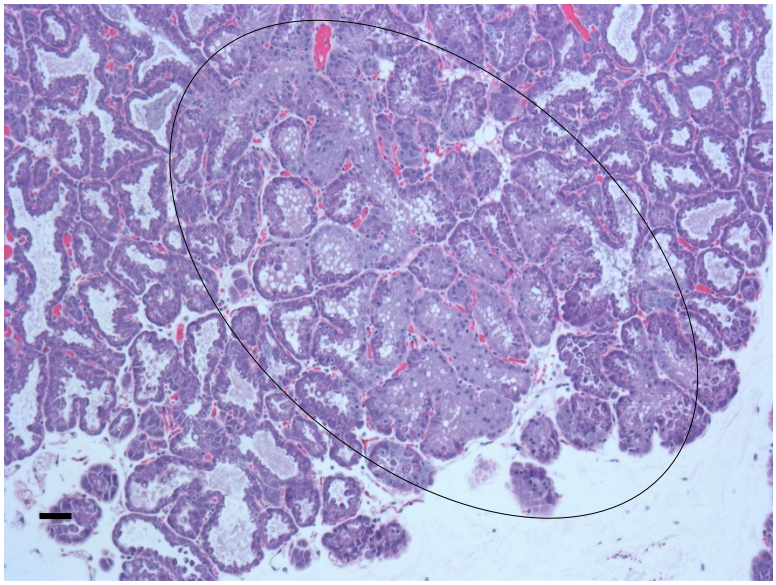
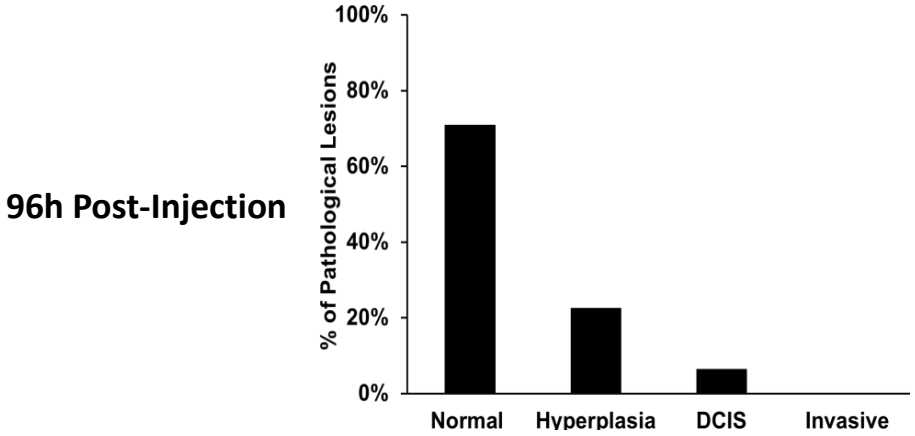


Figure 5. Effect of pregnancy on T47D and MCF7 tumor progression. (5A) T47D cells were evident in mammary ducts in mammary glands, but no distinct tumors were seen. (5B) Putative areas of MCF7 tumor development were also seen in the pregnant mammary microenvironment, but not as prominent as that seen in nulliparous glands (see Figure 4B). Scale bars = 50 um. Magnification = 10X.

6A



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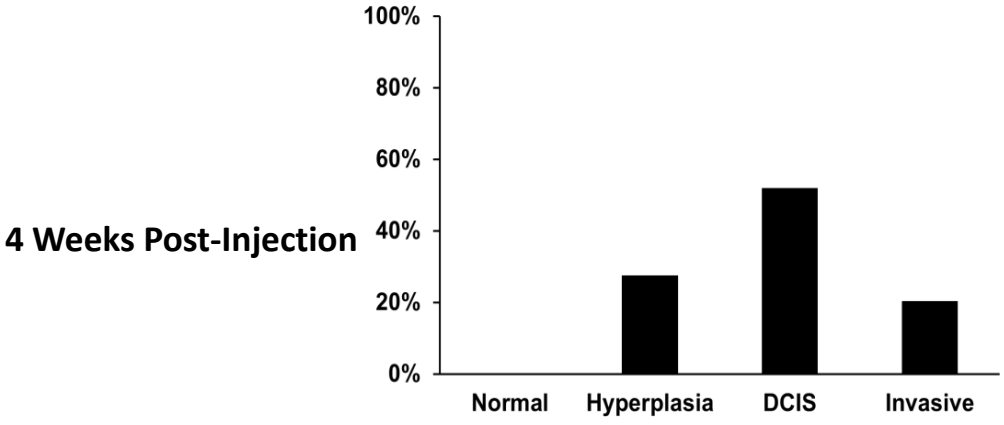

6C

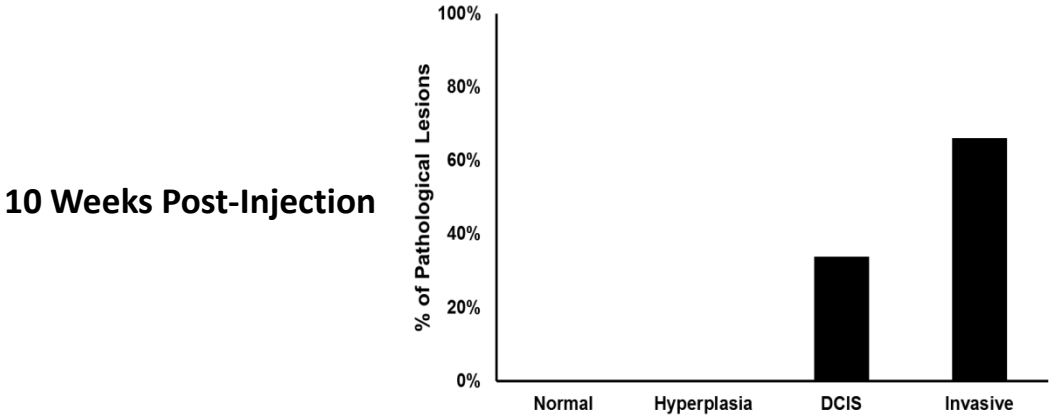

Figure 6. Quantative analysis of tumor progression in nulliparous mouse mammary glands. (6A) More hyperplastic/normal (3-4 tumor cell bolus) lesions are seen 96-hours post-injection, whereas more DCIS lesions are present 4 weeks post-injection (6B). (6C) At 10 weeks, more invasive lesions are seen.

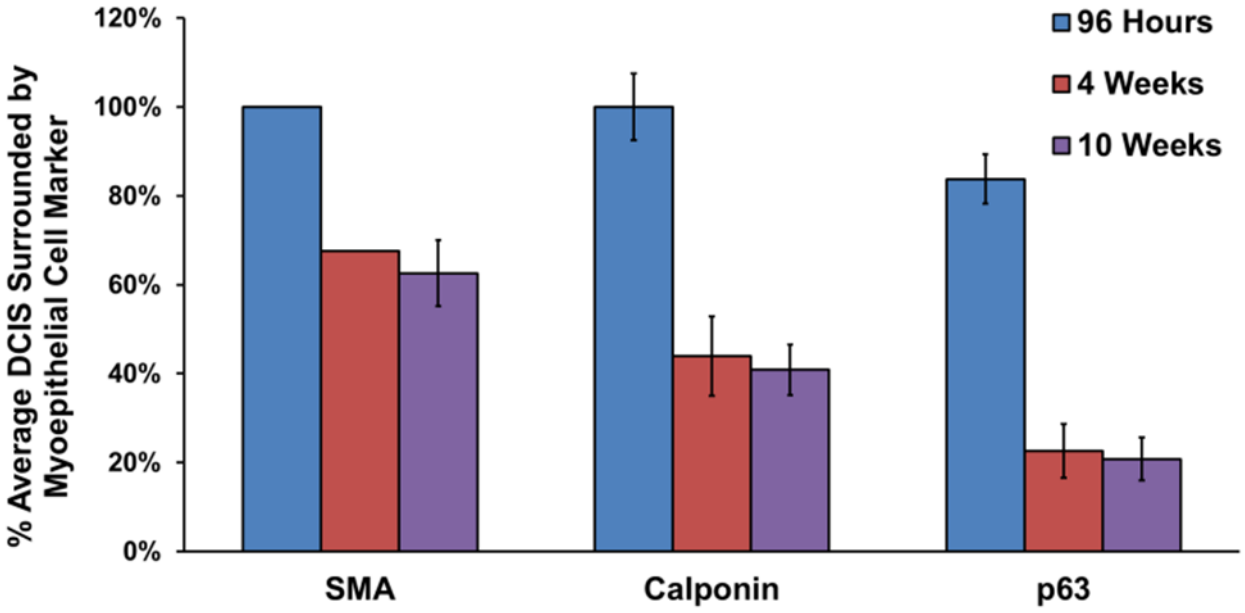

Figure 7. Anaylsis of DCIS surrounded by myoepithelial cell markers during early tumor progression. Mouse mammary glands intraductally injected with MCF10ADCIS.com cells were harvested 96 hours (blue), 4 weeks (red) or 10 weeks (purple) post injection and processed for IHC analysis of SMA, calponin, and p63. Myopepithelial cell layer is compromised early during DCIS progression of MCF10ADCIS.com tumors. Error bars = SEM.

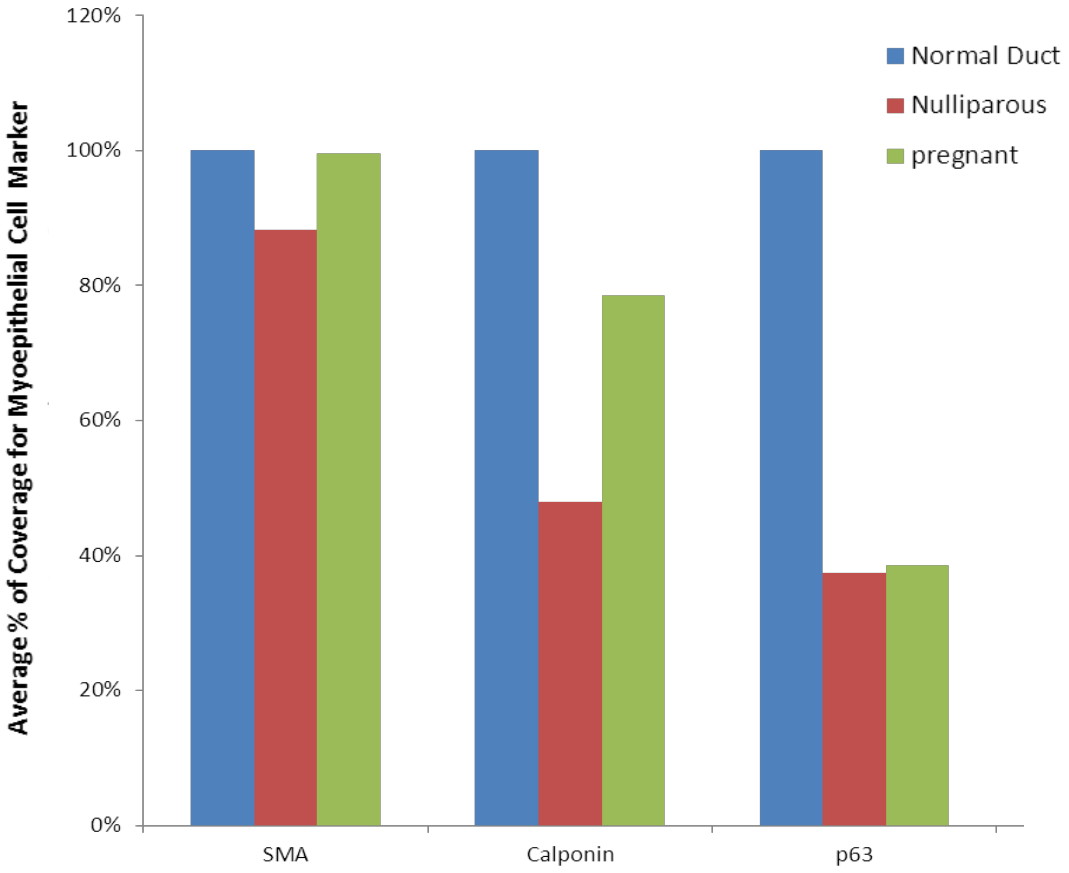

Figure 8. Progressive myoepithelial cell layer loss during pregnancy. Mouse mammary glands from nulliparous and pregnant mice were intraductally injected with MCF10ADCIS.com cells and harvested 4 weeks post injection. IHC analysis shows that SMA, calponin, and p63 surrounding normal ducts (blue) stay intact. SMA remains intact regardless of reproductive stage. Calponin and p63 surrounding DCIS in nulliparous mammary glands (red) are both decreased, while calponin surrounding DCIS in pregnant mammary glands (green) remain relatively intact.

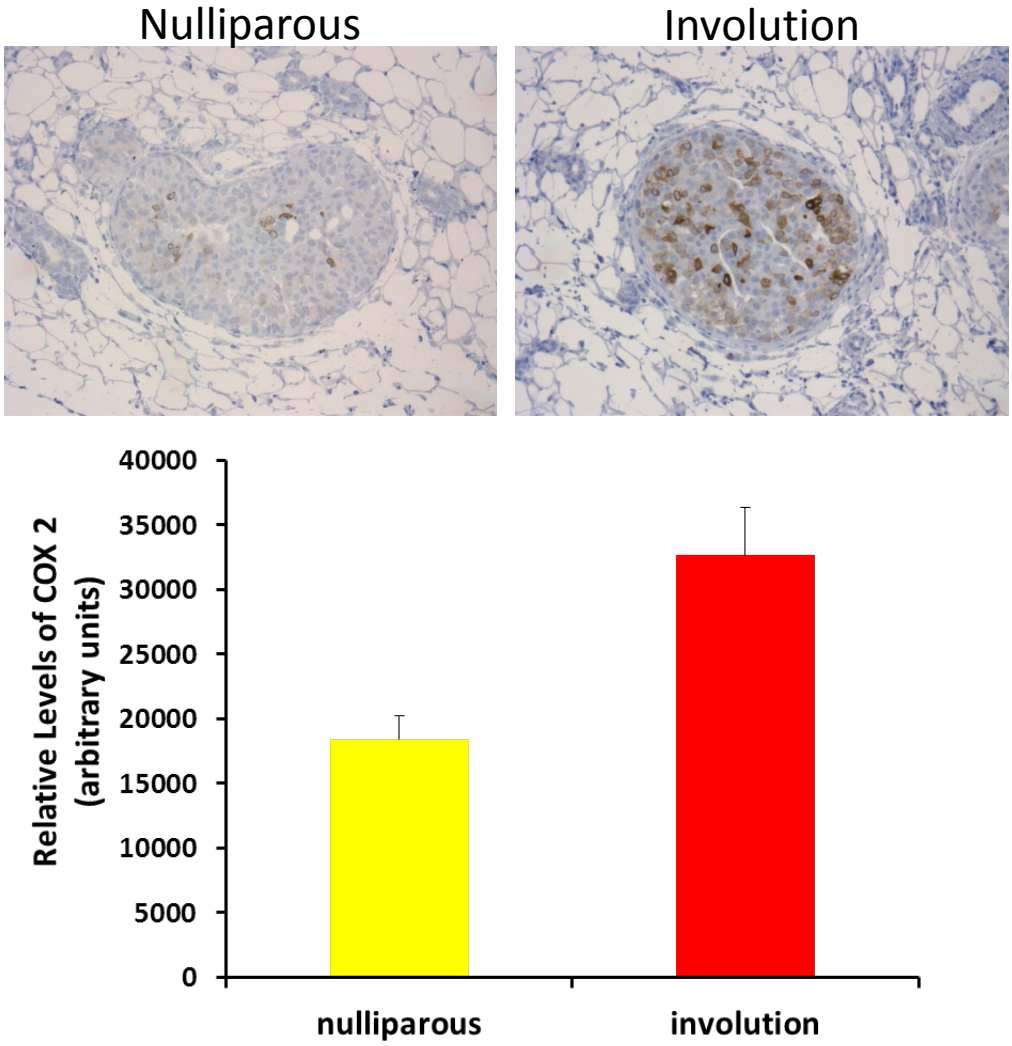

Figure 9. Effect of post-partum involution on COX2 expression in MCF10ADCIS.com tumors. (1A) IHC analysis shows COX2 (brown) expression in MCF10ADCIS.com tumors in nulliparous (left panel) and involution group (right panel) mouse mammary glands. (1B) COX2 expression in MCF10ADCIS.com cells in the involution group is higher than that of the respective nulliparous group. Error bars = SEM.

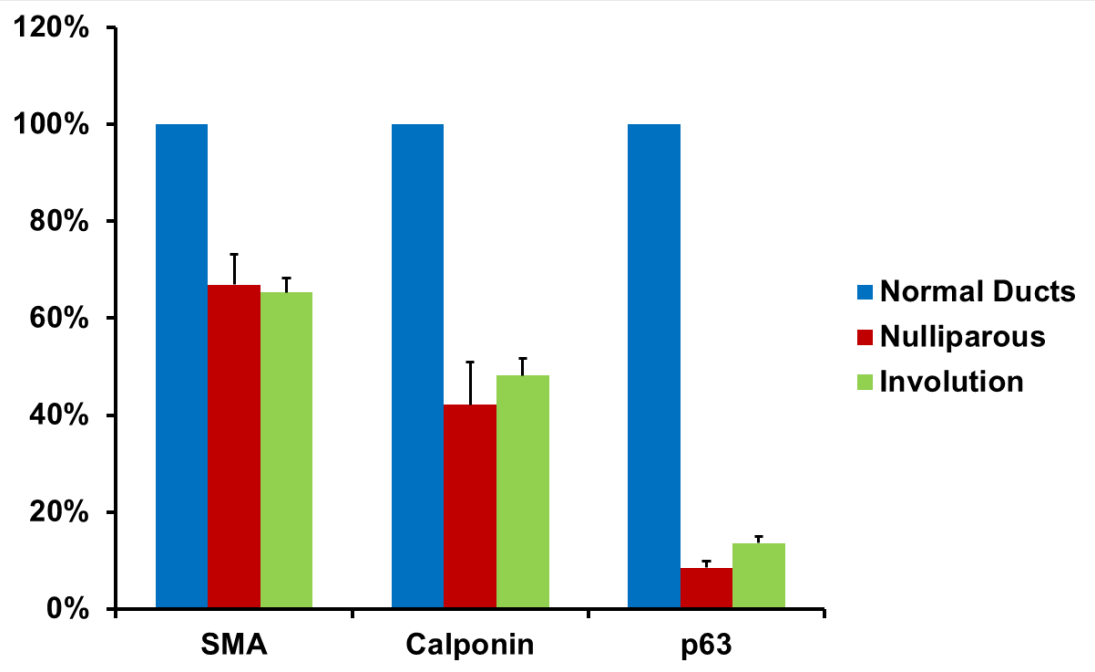

Figure 10. Progressive myoepithelial cell layer loss during post-partum involution. Mouse mammary glands were intraductally injected with MCF10ADCIS.com cells and harvested 4 weeks post injection. IHC analysis shows that SMA, calponin, and p63 surrounding normal ducts (blue) stay intact. SMA remains relatively intact surrounding tumors in nulliparous (red) and involution (green) group mammary glands. Calponin and p63 surrounding DCIS are decreased in both nulliparous (red) and involution group mammary glands (green) are decreased. Error bars = SEM.

TITLE PAGE

Title: Evidence for progressive loss of myoepithelial cell markers with DCIS progression to invasive disease

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ABSTRACT

We describe a preclinical model that permits investigation of early-stage ductal carcinoma in situ (DCIS) progression. DCIS.com cells are delivered into the intact mouse mammary teat by intraductal injection without surgical manipulation, which does not compromise ductal integrity and avoids wound-healing confounders. Using histochemical approaches, mammary glands were evaluated for tumor pathology, tumor growth, and myoepithelial cell layer integrity four and ten weeks post-injection. DCIS-like lesions develop throughout the glands with full representation of human DCIS histologic patterns, which appear to develop from hyperplasia to invasive ductal carcinoma. DCIS progression occurred with a progressive loss of key myoepithelial cell differentiation markers, smooth muscle actin, calponin, and p63. The loss of p63 was an early indicator of compromised myoepithelium and loss of calponin and smooth muscle actin as later indicators. A similar pattern of progressive loss of these myoepithelial cell markers was also seen in five human breast cancer cases. Thus, our murine intraductal model provides a rigorous approach to the study of early-stage breast cancer progression as demonstrated by the ability to assess tumor cell incorporation into normal mouse epithelium and by changes in myoepithelial markers.

KEYWORDS

murine mammary gland, intraductal, human DCIS, tumor progression, myoepithelial cell

INTRODUCTION

There is clinical evidence for histological progression of breast cancer through atypical hyperplasia, ductal carcinoma in situ (DCIS), invasive ductal carcinoma and metastatic stages [1]. Such histopathologic progression studies, as well as mutational profiling of epithelial cancers, suggest that acquisition of invasive potential is a relatively late event. However, genomic data analyses has revealed that the majority of tumor cell expression changes occur at the transition from normal to non-invasive DCIS, with very few additional changes in gene expression occurring at the transition from DCIS to overt invasive disease [2, 3]. These observations implicate key roles for non-epithelial cells in progression to invasion [4, 5]. To date, the lack of relevant model systems investigating early events in tumor progression hinders our understanding of the DCIS to invasive switch.

The clinical definition of invasive breast cancer is spread of malignant tumor cells from the confines of the mammary duct into the adjacent tissue stroma. In the normal mammary gland, epithelial ductal and alveolar structures are surrounded by a contractile myoepithelial cell layer which facilitates milk expulsion during lactation [6]. The mammary myoepithelial cells are also required for normal mammary gland development, as they influence epithelial cell polarity, ductal branching and milk production [6]. A hallmark of progression from DCIS to invasive cancer is physical breach of this myoepithelial cell layer. With respect to tumor progression, recent studies suggest that myoepithelial cells play an active role in tumor suppression by secreting protease inhibitors, down regulating matrix metalloproteinases [7-11], and producing tumor suppressive proteins such as maspin, p63, Wilm's tumor 1, p73 and 14-3-3Sigma [10-15]. These data support the hypothesis that the tumor suppressive function of the myoepithelium is lost with tumor progression, resulting in the transition from a pre-invasive to an invasive cancer

[9, 10]. Another hypothesis posits that tumor cells and/or accumulation of other reactive non-epithelial cells, such as fibroblasts or immune cells, lead to the physical breakdown of the myoepithelial barrier and "escape" of malignant epithelial cells [9, 10, 16]. Studies have reported that DCIS-associated myoepithelial cells are phenotypically different than normal myoepithelial cells [4, 8]; and tumor cells adjacent to focal myoepithelial cell layer disruptions can display distinct phenotypes including estrogen receptor (ER) negativity, genetic instabilities, increased expression of invasion-related genes, and aberrant E-cadherin expression [16-18]. Overall, these data support both active and passive roles for the myoepithelium in DCIS progression, and further suggest interplay between tumor cells and the myoepithelial cells contribute to loss of the myoepithelial cell layer that is critical for the transition to invasive disease.

To date, tumorigenic potential of human mammary epithelial tumor cell lines is primarily evaluated by injecting cells into the mammary fat pads of immune compromised mice [19]. While the mammary fat pad (MFP) is the correct organ host for invasive breast cancer, it is not the correct anatomical location for early stage, pre-invasive tumors. With respect to tumor progression, MFP models bypass the requirement for tumor cells to exit from the location of their initiation, i.e., the mammary ducts. Alternatively, transgenic models offer correct anatomical location of breast cancer and display tumor progression from initiation to hyperplasia to invasive stages, but since all epithelial cells contain the active oncogene, these models do not replicate transformation as a rare event. For this report, we utilized an intraductal approach in the absence of surgery [20], as this approach offers a key advantage in that cells are directly placed in the correct anatomical location where tumor initiation occurs. This approach also permits modeling of disease progression in the background of a normal mammary epithelium. Further,

this approach permits co-evolution of tumor progression with myoepithelial cell changes with minimal wound healing or pro-inflammatory induction.

MATERIALS AND METHODS

Animals

5-week old female nulliparous SCID mice were obtained from Taconic (Hudson, NY) and maintained in the Center for Laboratory Animal Care at the University of Colorado Anschutz Medical Campus. Intraductal tumor inections were performed as described below. Mammary tissue was excised from animals euthanized by carbon dioxide exposure followed by cervical dislocation. All animal procedures were approved by the Institutional Animal Care and Use Committee of the University of Colorado Anschutz Medical Campus (protocol #72110(07)1E).

Cell Culture

DCIS.com cells and GFP-labeled DCIS.com cells (a generous gift from Kornelia Polyak) were cultured as previously described [8] and resuspended in PBS immediately prior to injection. Cells were used between passages 8 – 22, as passages later than 22 have been shown to display a more invasive phenotype [21]. T47D, MCF7, and HCC70 cells were obtained from the University of Colorado Cancer Center Protein Production/Mab/Tissue Culture Core and cultured as recommended by the supplier.

Intraductal Injections for Tumor Studies

Mice were anesthetized using isofluorane delivered by a portable anesthesia machine. 3-10µl of 50,000 DCIS.com, T47D, MCF7, or HCC70cells, were intraductally injected into anesthetized mice using a previously described intraductal delivery method developed for viral delivery [20, 22]. Briefly, the end of a 25µl Wiretrol II disposable glass micropipette (no. 5-000-2050; Drummond Scientific Company, Broomall, PA) was drawn and fire-polished into a fine tip of

60-75μm. Sterile cell solution was loaded into the micropipette with a stainless steel plunger. Using a micromanipulator, the tip was gently inserted directly into the teat canal and cells slowly ejected into the lumens of the left third thoracic and both fourth inguinal mammary glands of mice (n = 3-4 injected glands /mouse). Images depicting the intraductal injection technique were captured using a Canon PowerShot A620 camera with 4X optical zoom. For injections with T47D and MCF7 cells, anesthetized mice received a sterile placebo implant (Innovative Research of America,Sarasota, FL, cat. no. SC-111 or 0.72 mg 17beta-estradiol (InnovativeResearch of America, Sarasota, FL, cat. no. SE-121). The insertion area (dorsal side of neck between the shoulder blades) was shaved and swabbed with chloriheximide digluconate solution. Pellets were inserted with a sterilized 10-gauge stainless steel precision trochar (Innovative Research of America, Sarasota, FL, cat. no. MP-182).

Immunohistochemistry, Imaging, and Quantification

Excised mouse mammary glands were fixed in 10% NBF, paraffin embedded , and prepared for hemotoxylin and eosin staining as previously described [23]. Briefly, entire histological sections were scanned as described and total tumor number and area were quantified using Aperio Spectrum software (Aperio Techologies, Vista, CA). For immunohistochemistry, 4μm sections of paraffin embedded mouse mammary gland tissue were pretreated with Dako TRS Antigen Retriveal Solution (TRS) or Dako EDTA Antigen Retrieval Solution (EDTA). Research using de-identified human breast tissue was conducted under a protocol with individual subject consent as approved by the Colorado Multiple Institution Review Board (COMIRB) and tissues were acquired as previously reported [23]. The following antibodies, antigen retrievals, and antibody dilutions were used: mouse anti-human E-cadherin (TRS, 1:100; Cell Signaling, Danvers, MA),

mouse anti-human p63 (EDTA, 1:200; BioCare Medical, Concord, CA), mouse anti-human cytokeratin 5 (CK5) (EDTA, 1:50; BioCare Medical, Concord, CA), rabbit anti-human calponin (EDTA, 1:800; Abcam, Cambridge, MA), mouse anti-human smooth muscle actin (SMA) (EDTA, 1:200; Dako). ER positivity was assessed according to the Allred scoring method [24]. HER2 positivity was determined using the FDA approved Hercep test for the Dako Autostainer.

Hemotoxylin and eosin stained slides were used to assess the distribution of tumor emboli, hyperplasias, DCIS, DCIS with focal disruptions, and invasive lesions for mouse mammary glands and human breast tissues. Tumor emboli were defined as 1-5 layers of tumor cells within mammary ducts without direct contact. Hyperplasias were defined as less than six layers of tumor cells tapering normal mouse or human ductal epithelium [25]. DCIS lesions were assessed by size and architectural patterns of proliferation [26]. DCIS with focal disruptions was defined as an absence of myoepithelial cells and evidence of tumor cells outside of the confines of the disrupted mammary duct. Invasive lesions were defined as tumor cell infiltrating the mammary stroma.

For myoepithelial cell layer integrity quantitation, tumor associated myoepithelial cell expression of SMA, calponin, and p63 was obtained using serial IHC sections. The surrounding normal terminal ductal-lobular units served as internal positive controls for the above mentioned myoepithelial biomarkers. Data is presented as average percent coverage of tumors/group suurounded by myoepithelial cell markerpositivity (arbitrary cutoff), with 25 tumors per group analyzed. Data was analyzed by two independent assessments followed by concurrent review and correlation with an Aperio deconvolution algorithm.

Fluorescent In Situ Hybridization (FISH) Analysis

FISH analyses were performed using probes for human and mouse Cot-1 DNA, as previously described [27], by the University of Colorado Cancer Center Cytogenetics Core.

Statistical Analysis

Mixed effects Analysis of Variance were used to compare normal and for each biomarker (SMA, calponin, and p63) at 4 and 10 weeks, and also to also compare DCIS at 4 weeks vs 10 weeks and DCIS with focal disruption at 4 weeks vs 10 weeks. The possible correlation among the biomarker measures on tumors from the same mouse was taken into account of consideration. P-value justification for multiple comparisons was done following Bonferroni's approach. $P<0.05$ was considered statistically significant throughout the paper.

RESULTS AND DISCUSSION

Validation that the Intraductal Model Preserves Mammary Duct Integrity

To deliver breast cancer cells to the correct anatomical location for DCIS, we modified a non-surgical injection model previously developed for intraductal viral delivery [20, 22]. Human triple negative DCIS.com cells [21] were intraductally injected into an intact teat of nulliparous mice in the absence of any surgical manipulation (see Supplemental Data). This approach minimizes surgery-induced inflammation as a study potential confounder [28-31]. Since progression to invasive disease requires disruption of normal epithelial junctional integrity as well as loss of the myoepithelial cell layer, we first verified that ductal integrity is not compromised during intraductal tumor cell delivery. GFP-labeled DCIS.com cells [32] were injected at 2.5 µl (Figure 1A, a,b,c), 5.0 µl (Figure 1A, d,e,f), or 10 µl volumes (Figure 1A, g,h,i) and the effect of the different injection volumes 24 hours post-injection on the integrity of the epithelial and myoepithelial cell layers was determined by assessing the presence of GFP-labeled cells within the mammary stroma and by immunohistochemical (IHC) detection of ductal epithelial E-cadherin and myoepithelial smooth muscle actin (SMA), respectively. For all three injection volumes, there was no evidence of GFP positive tumor cells within the mammary stroma (Figure 1A, a,d,g), no visible signs of disruption of the epithelial E-cadherin junctional complexes (Figure 1A, b,e,h), and no evidence of disruption in the myoepithelial cell layer (Figure 1A, c,f,i). However, whether or not junctional integrity is functionally compromised in the mammary gland via intraductal injection cannot be fully addressed using IHC. Previous studies have analyzed tight junction permeability of mammary epithelial cells during secretory activation by intraductally injecting ^{14}C-sucrose and measuring its presence in the blood [33, 34]. Thus, we assessed ^{14}C-sucrose permeability in nulliparous glands and found that while injected

dye volumes of 5 µl do not appear to compromise ductal integrity, volumes of 10 µl or greater may disrupt junctional complexes (see Supplemental Data). Therefore, for subsequent studies, we elected a 5 µl volume of tumor cells as an optimal volume for intraductal teat injection into nulliparous hosts.

To assess the whether other human breast cancer cell lines can establish tumors when intraductally injected into murine mammary ducts, we analyzed tumor formation and progression of two luminal A cell lines, T47D and MCF7, as well a second triple negative cell line, HCC70 [35]. T47D cells did not form tumors in the absence or presence of supplemental estradiol, however a few viable cells persisted in mammary lumens at the 4 weeks post-injection time point (Figure 2A, a,b). MCF7 cells failed to form tumors in the absence of estradiol, but readily formed solid (Figure 2A, c,) and comedo (Figure 2A, d) DCIS lesions in the presence of supplemental estradiol. The triple negative cell line HCC70 also formed robust tumors in the absence of estradiol supplementation, which were mostly solid DCIS with high mitotic activity (Figure 2A, e). Based on these data, the intraductal model permits the intraductal growth of ER positive and ER negative breast cancer cell lines.

Evidence of Histologic Patterns of Tumor Progression

Our histological analysis of DCIS.com intraductal tumors corroborate and extend previous observations by showing DCIS lesions that display characteristics of the main human DCIS subtypes: solid, cribriform, pseudo-papillary, and comedo (Figure 2B, a-d) [8, 21, 36, 37]. Importantly, intraductal DCIS-like lesions utilize the endogenous mouse myoepithelial layer (Figure 2C, b, arrows), and do not generate a human cell derived myoepithelial cell layer as observed in subcutaneous and MFP models [8, 21, 38] [36]. Unique to the intraductal delivery model, we observe that normal ductal structures can be composed primarily of the human

DCIS.com cells (Figure 2C, a), as well as incorporate into the normal mouse ductal epithelium (Figure 2C, b), as detected by fluorescent in situ hybridization (FISH) using probes specific for human (red) and mouse (green) COT-1 DNA [27]. We next evaluated whether DCIS.com cells form E-cadherin-based adherens junctions with neighboring mouse epithelial cells within the mammary duct, as formation of adherens junctions would suggest that very early stage tumor lesions develop in this model [39]. This analysis shows that DCIS.com cells form E-cadherin based junctional complexes with normal mouse epithelial cells, as well as with neighboring tumor cells, albeit at a lower staining intensity (Figure 2C, c,d). Confirmation of these junctional complexes highlights the relevance of this model for the study of tumor cell escape/invasion out of intact mammary ducts. Finally, we observe that DCIS.com cells breach the mouse myoepithelial cell layer and locally invade into adjacent stroma (Figure 2D).

To investigate disease progression in this model, we quantified the number of tumor emboli (Figure 3A, a), hyperplasias (Figure 3A, b), DCIS lesions (Figure 3A, c), DCIS with focal disruption (Figure 3A, d), and overt invasive lesions (Figure 3A, e), at 96 hours, 4 weeks, and 10 weeks post injection. Tumor cell emboli were predominant at 96 hours post-injection, comprising 70% of the mammary gland lesions, followed by hyperplasias and DCIS-like lesions (Figure 3B). The distribution of lesions shifted from emboli towards DCIS and invasive disease at 4 weeks (Figure 3B, both panels), with evidence for further progression by 10 weeks (Figure 3B, left panel). To interrogate potential relevance to human DCIS, we quantified hyperplastic ducts, DCIS, DCIS with focal disruptions, and invasive lesions (see Methods) in five premenopausal human breast cancer cases, two of which were diagnosed with DCIS in the absence of invasive ductal carcinoma. Similar to our intraductal DCIS model, we find histologically comparable lesions of hyperplasia, DCIS and DCIS with focal disruption present

within each case (Figure 3C, a,b,c). Within a single case, we observe varying distributions of hyperplasia, DCIS, and DCIS with focal disruption or invasive lesions (Figure 3D). Further, the distribution of lesions was similar to those formed 4 weeks post intraductal injection (Figure 3B, right panel). The similarities in mammary lesion type and distribution between our intraductal model and human cases further demonstrate the capacity of the model to serve as a tool to investigate human DCIS progression.

Characterization of Myoepithelial Cells with DCIS Progression

Loss of the myoepithelial cell layer is a hallmark of DCIS progression to invasive disease [7, 40]. However, the question of whether myoepithelial cells progressively lose markers associated with myoepithelial cell function has not been systematically investigated. Here, we used IHC to assess a panel of myoepithelial cell specific markers, SMA, a major contractile protein; calponin, a calcium binding cytoskeletal protein [41-43]; and the transcription factor p63, a putative tumor suppressor [8, 12, 44], to access changes with early stage DCIS progression. In normal myoepithelial cells from non-tumor bearing ducts, as expected, there is evidence for uniform SMA, calponin and p63 expression (Figure 4A, a, b, c). However, variable expression of these myoepithelial cell markers was seen surrounding intact DCIS lesions (Figure 4A, d,e,f,) and DCIS with focal disruption (Figure 4A, g,h,i). Quantification of these data shows that all three markers are expressed in the vast majority of myoepithelial cells lining the normal ducts (Figures 4B and 4C). At the 4 week time point, in DCIS lesions with a morphologically intact myoepithelial cell layer, 85% express SMA, 70% express calponin and only 8% of myoepithelial cells express p63 (Figure 4B) inferring differential loss of these myoepithelial cell markers within DCIS lesions. Further, there is significantly decreased coverage of all three markers in DCIS with DCIS with focal disruptions (Figure 4B). These data suggest that within

DCIS lesions arising from the same duct(s), myoepithelial cells exhibit molecular diversity with evidence for progressive loss of function with DCIS progression. Additional evidence suggesting that myoepithelial cell function is lost with DCIS progression is found at the 10 week time point, where coverage significantly declines ($P < 0.0001$) for SMA (78%) and calponin (44%) , compared to the 4 week time point (Figure 4C). Further, loss of p63 in the myoepithelial cell layer now correlates with gain of p63 in the tumor cells, indicating progression within the tumor cell compartment as well (compare Figures 4A f and i).

We next evaluated whether similar trends in SMA, calponin, and p63 loss are observed in human DCIS lesions. Similar to the intraductal model, variable expression of these markers were seen in myoepithelial cells surrounding human DCIS lesions; some myoepithelial cells displayed high levels of SMA, calponin, and p63 (Figure 5A, a-c) whereas others lacked expression of these markers (Figure 5A, d-f). While each case has a unique SMA, calponin and p63 expression profile, a similar trend in myoepithelial cell marker loss is observed (Figure 5B, a-e). Composite analysis of all five cases demonstrates that in myoepithelial cells surrounding DCIS lesions, p63 expression is significantly less than calponin ($P < 0.0001$), which is significantly less than SMA ($P < 0.0001$) (Figure 5B, f). These data show sequential loss of expression of p63, calponin and SMA prior to overt loss of the myoepithelium and are consistent with the notion that loss of the myoepithelium plays a key role in the transition of non-invasive to invasive disease.

CONCLUSIONS

Our preclinical intraductal model of human DCIS provides a rigorous approach to study early events in breast cancer progression from ductal hyperplasia to breach of the myoepithelial cell layer, stages of disease not amenable for study in the commonly utilized MFP xenograft models. An intraductal approach recently described by Harrell et al offers a major advancement over MFP models by depositing cells in a large volume (200µl) within the surgically exposed lactiferous duct. This model permits lymph node metastasis, which is not commonly observed in MFP models [45]. However, our data using epithelial cell tight junction disruption as a marker for loss of epithelial integrity demonstrate that the normal ductal networks within the mammary gland are likely disrupted with injection volumes exceeding 10µl. Thus "large volume" intraductal methods may bypass tumor cell incorporation into the ductal epithelium of the host mammary gland and not permit the investigation of early changes in the myoepithelial cell layer that occur with tumor progression. Another published intraductal model injects a small volume of tumor cells, thus preserving duct integrity, but surgical manipulations are used to cleave the teat and expose the main lactiferous duct [36, 46]. These surgical procedures may induce localized wound-healing and inflammatory programs shown to be tumor promotional in other contexts [28-31]. Here, we describe an intraductal model that minimizes wound-healing programs and inflammation, and which may permits the evaluation of subtle physiologic changes on DCIS progression. A limitation to the method described here, and all other human breast cancer models, is the requirement for immune deficient animals. The application of our intraductal approach to isogenic models would permit investigation of DCIS progression in an immune competent host.

The intraductal model described here permits a rigorous evaluation of early molecular changes within the mammary myoepithelium, which serves as a barrier to invasive cancer. Our data, demonstrating that DCIS lesions with an intact myoepithelial cell layer display progressive loss of specific myoepithelial cell markers, suggest that the myoepithelium is compromised prior to DCIS progression to invasive disease. We focused our initial studies on three myoepithelial cell markers: SMA, calponin, and p63, loss of which are commonly used to identify DCIS progression to invasive disease [47-49]. With DCIS progression, SMA positivity surrounding tumors remains relatively stable even at 10 weeks post intraductal injection (Figure 4C), suggesting that the actin cytoskeletal architecture detected with anti-SMA antibody may be a stable feature, with total loss of SMA positivity around DCIS-like lesions occurring upon physical loss of myoepithelial cells. Conversely, calponin, an important actin cytoskeleton regulator [50-52], shows more frequent loss within myoepithelial cells; being present in lesions 4 weeks post injection (Figure 4B) and reduced in lesions with an intact myoepithelial cell layer by 10 week post injection (Figure 4C). The role of calponin in tumor progression poorly understood. Calponin may play a tumor suppressive role in human leiomyosarcoma by inhibiting signaling pathways important for cell morphology, growth and spreading [52, 53] and metastatic cell motility [54]. Expression of calponin has also been shown to reduce tumorigenesis and cell motility in osteosarcoma, fibrosarcoma, aggressive adenocarcinoma and melanoma cell lines [52]. With further research efforts, calponin has the potential to serve as a useful therapeutic target for breast cancer progression.

We show that p63 expression in myoepithelial cells is lost prior to calponin, further indicating a compromise in myoepithelial cell differentiation that may facilitate the transition to invasiveness. A critical function of p63 is the development and maintenance of stratified

squamous epithelial tissue; $p63^{-/-}$ mice completely lack mammary epithelial tissue and $p63^{+/-}$ mice are highly susceptible to spontaneous tumor formation in multiple organs [55, 56]. p63 is also an important regulator of terminal differentiation and polarity of both epidermal and myoepithelial cells and disruption of these processes have been shown to promote progression of DCIS to invasive cancers [2, 57]. It remains to be determined whether decreased expression of myoepithelial cell p63 leads to loss of polarity of mammary epithelial cells. This p63-mediated polarity disruption could potentially increase the chance for metastasis. However, intratumoral p63 is also evident in DCIS lesions formed by DCIS.com cells, indicating acquisition of basal-like attributes [58, 59] with progression (Figure 4f, i). Upregulation of p63 in DCIS lesions formed by DCIS.com cells has been previously shown to occur near regions of compromised myoepithelium [38]. An increase of p63 in tumor cells may lead to subsequent decrease in p63 in myoepithelial cells through currently unknown mechanisms. Recent data by Lee and colleagues demonstrated that DCIS.com cells highly express dystonin a candidate tumor suppressor gene [2]. Dystonin is a cytoplasmic protein involved in cell adhesion, cytoskeletal organization, polarity, and is directly regulated by p63 in keratinocytes [2]. Since p63 plays an important role in maintaining myoepithelial cell polarity and differentiation, a link between DST and p63 may provide insight into DCIS to invasive cancer progression.

Our model can be defined as a multifocal model of tumor progression incorporated into distinct ductal regions. Upon analysis of human breast cancer sections, similar heterogeneity in lesion types was observed (Figure 3C). Given the similarities in the distribution of lesions observed between the intraductal model and human disease, it is anticipated that this model will begin to uncover the intricate details of tumor progression as it is defined from non-life threatening DCIS to overt invasive disease. In particular, we observed comedo-DCIS lesions in

two different breast cancer cell lines (Figures 2A, d and 2B, d) which differ from other types of DCIS in hormone receptor and Her2/neu status [60, 61]; higher grade [26]; higher risk for ipsalateral tumor recurrence [60]; and may serve as precursors for aggressive basal-like breast cancers [62]. It is possible that the genetic alterations that determine the tumorigenic fate of a cell may alter the ability of tumors to interact with the myoepithelium. Evidence that myoepithelial cells progressively lose function associated with tumor suppression may provide novel insight into DCIS progression that could be harnessed for risk assessment. Given the nature of DCIS as precursors to invasive disease, we anticipate that myoepithelial cell molecular profiling will also yield insight into the mechanisms regulating the transition of DCIS to invasive disease. Further, by investigating the influence of distinct tumor cell populations on myoepithelial cell function, important cellular crosstalk pathways can be elucidated and targeted for intervention.

In summary, our preclinical intraductal model of human breast cancer provides a rigorous, approach to studying tumor progression from early stage hyperplasia to invasion. Since tumor cells are delivered in the absence of surgical manipulation, this model is particularly suited to studying the subtle effects of host physiology on DCIS progression. Since occult tumors in women develop within ducts, we propose that this teat injection model will facilitate research of early disease progression, a requisite for research focused on breast cancer prevention and inhibition of local invasion.

ABBREVIATIONS:

DCIS	ductal carcinoma in situ
ER	estrogen receptor
MFP	mammary fat pad
FISH	fluorescent in situ hybridization
SMA	smooth muscle actin
CK5	cytokeratin 5

COMPETING INTERESTS: We have no competing interests to declare.

AUTHORS' CONTRIBUTIONS

TDR designed and performed all animal experiments, performed the intraductal injections, IHC, ^{14}C-sucrose experiments, interpreted and analyzed data, and prepared the manuscript. SA performed the majority of IHC experiments, and provided extensive data collection and analysis. SJ provided translational research guidance, IHC human tissue analysis, interpreted and analyzed human data. DG conducted the statistical analyses. VB provided access to human tissue. PS supervised the project, designed experiments, interpreted results, and made substantial contributions to manuscript preparation.

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FIGURE LEGENDS

Figure 1. Ductal and myoepithelial cell layer integrity is not compromised by the intraductal injection method. A. GFP-labeled DCIS.com cells were injected at volumes of 2.5 µl (panels a-c), 5.0 µl (panels d-f), and 10 µl (panels g-i) to assess junctional complex and myoepithelial cell layer disruption. Serial sections were stained with GFP to confirm the presence of human tumor cells (brown, panels a, d, g); E-cadherin to assess ductal epithelia junctional complex disruption (brown, panels b, e, h); and SMA to assess myoepithelial cell layer disruption (brown, panels c, f, and i). Images scanned using Aperio software. Digital resolution = 0.25µ/pixel. Scale bar = 100um.

Figure 2. Assessment of cell lines injected via the mammary intraductal model. A. Serial hemotoxylin and eosin (H&E) (a) and fluorescent in situ hybridization (FISH) analyses for human (red) and mouse (green) COT-1 DNA (b) of nulliparous mouse mammary glands injected with T47D breast tumor cells in the absence of estradiol via intraductal method. Magnification = 40X. Representative H&E images display the solid (c) and comedo (d) characteristics of human DCIS formed from MCF7 cells only in the presence of estradiol. Images scanned using Aperio software; digital resolution = 0.25µm/pixel. H&E analysis of solid DCIS from HCC70 tumor cells (e) with high mitotic activity (arrows). Image scanned using Aperio software; digital resolution = 0.25µm/pixel. Scale bars = 50µm. B. H&E analysis of DCIS.com tumor cells injected via mammary intraductal method. Tumors formed from DCIS.com cells undergo stages of early tumor progression, displaying the different characteristics of human DCIS (solid – a; cribriform – b; pseudo papillary – c; comedo – d). Images scanned using Aperio software; digital resolution = 0.25µ/pixel. Scale bar = 80µm. C. Fluorescent in situ hybridization (FISH) analysis for human (red) and mouse (green) COT-1 DNA reveals tumor progression from normal-like ductal structures (a) to DCIS (b) with incorporation of human tumor cells into normal mouse mammary ducts (arrows). Magnification = 40X. Scale bars = 50µm. Serial FISH (c) and IHC analysis (d) of the cytoplasmic domain of E-cadherin (brown) suggest that E-cadherin-based junctional complexes form between DCIS.com cells (white arrows) and between DCIS.com cells and mouse ductal epithelial cells (arrowheads). Magnification = 100X. Scale bar = 20µm. D. DCIS.com cells can breach the normal mouse mammary myoepithelial cell layer and invade into the surrounding stroma. Image scanned using Aperio software; digital resolution = 0.25µ/pixel. Scale bar = 80µm.

Figure 3. Multifocal tumor progression model assessment. A. Representative H&E images of tumor progression reveal the formation of tumor emboli (a, arrows), hyperplasia (b, arrow), DCIS (c), DCIS with microinvasion (d, arrows), and overt invasion (e). Insets in panels a, b, and e are enlarged to show detail. B. Quantification of the percent pathological lesions at various post-injection time points showed tumor progression from mostly tumor emboli at 96 hours post-injection and DCIS 48 hours post-injection to invasive cancer at 10 weeks post-injection (left panel). The histopathological pattern at 4 weeks post-injection reflects tumor progression from hyperplasia to DCIS to invasive disease (right panel). C. Representative H&E images from a single slide of human breast cancer tissue show various stages of tumor progression from atypical hyperplastic lesions (a), to DCIS (b), to invasive disease (c). Images scanned using Aperio software; digital resolution = 0.43μ/pixel. Scale bar = 50 um. D. Quantification of the total number of pathological lesions present in five individual human cases show similar patterns that of the intraductal multifocal model at 4 weeks post-injection (B, right panel). Two of the human cases were clinically diagnosed with DCIS in the absence of invasive disease (d and e) and were assessed for total number of DCIS with focal disruption (DCIS-FD).

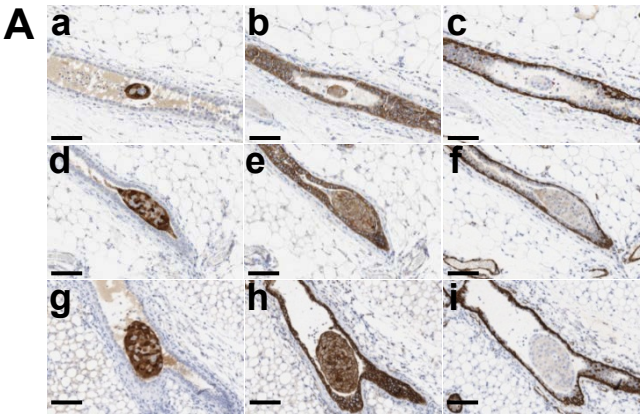
Figure 4. Progressive loss of myoepithelial cell differentiation markers in multifocal tumor progression model. A. Serial IHC analysis of myoepithelial cell markers SMA (panels a, d, and g; brown), calponin (panels b, e, and h; brown), and p63 (panels c, f, and I; brown). Insets in panels a-c are enlarged to show detail of normal mouse ductal structures. DCIS lesions (panels d-f) and DCIS with focal disruption (panels g-i) were assessed for myoepithelial cell marker coverage. Progressive loss of all three markers was evident and gain of p63 by tumor cells is also apparent (panels f and i). Images scanned using Aperio software. Digital resolution =

0.43μ/pixel. Scale bar =100μm. Quantification of the percentage of myoepithelial cell layer markers surrounding tumors, compared to the percentage of normal, non-tumor bearing ductal structures surrounded by myoepithelial cell layer markers at 4 weeks (B) and 10 weeks (C) post-injection. Statistical significance was determined by mixed effects Analysis of Variance and P-value justification for multiple comparisons using Bonferroni's approach. * $P<0.05$ comparing normal and DCIS. ** $P<0.05$ comparing normal and DCIS with focal disruption. ***$P<0.05$ comparing DCIS and DCIS with focal disruption. Solid bars = SEM.

Figure 5. Progressive loss of myoepithelial cell differentiation markers in human breast cancer. A. Representative serial IHC analysis of myoepithelial cell markers SMA (panels a and d; brown), calponin (panels b and e; brown), and p63 (panels c and f; brown) shows high expression in myoepithelial cells surrounding some DCIS lesions (panels a-c) and almost no expression in other lesions (panels d-f). Images scanned using Aperio software. Digital resolution = 0.43μ/pixel. Scale bar = 40um. B. Quantification of the percentage of myoepithelial cell layer markers surrounding DCIS obtained from five individual human cases. Statistical significance was determined by mixed effects Analysis of Variance and P-value justification for multiple comparisons using Tukey-Kramer approach. *$P < 0.0001$.

Supplemental Figure 1. Intraductal injection method. A. A small area surrounding the teat (arrow) was aseptically cleared of fur (a). A fabricated glass micropipette with 60-75µm tip diameter was then positioned near the intact teat (b) and carefully guided into the teat (inset arrows). B. Ductal epithelia tight junction permeability as a function of volume was assessed by intraductally injecting mice with the stated doses of Trypan blue dye mixed with [^{14}C]-sucrose in nulliparous mice. Each bar represents the average of [^{14}C] counts per minute (CPM) measured in the blood. n = 2/group.

Figure 1



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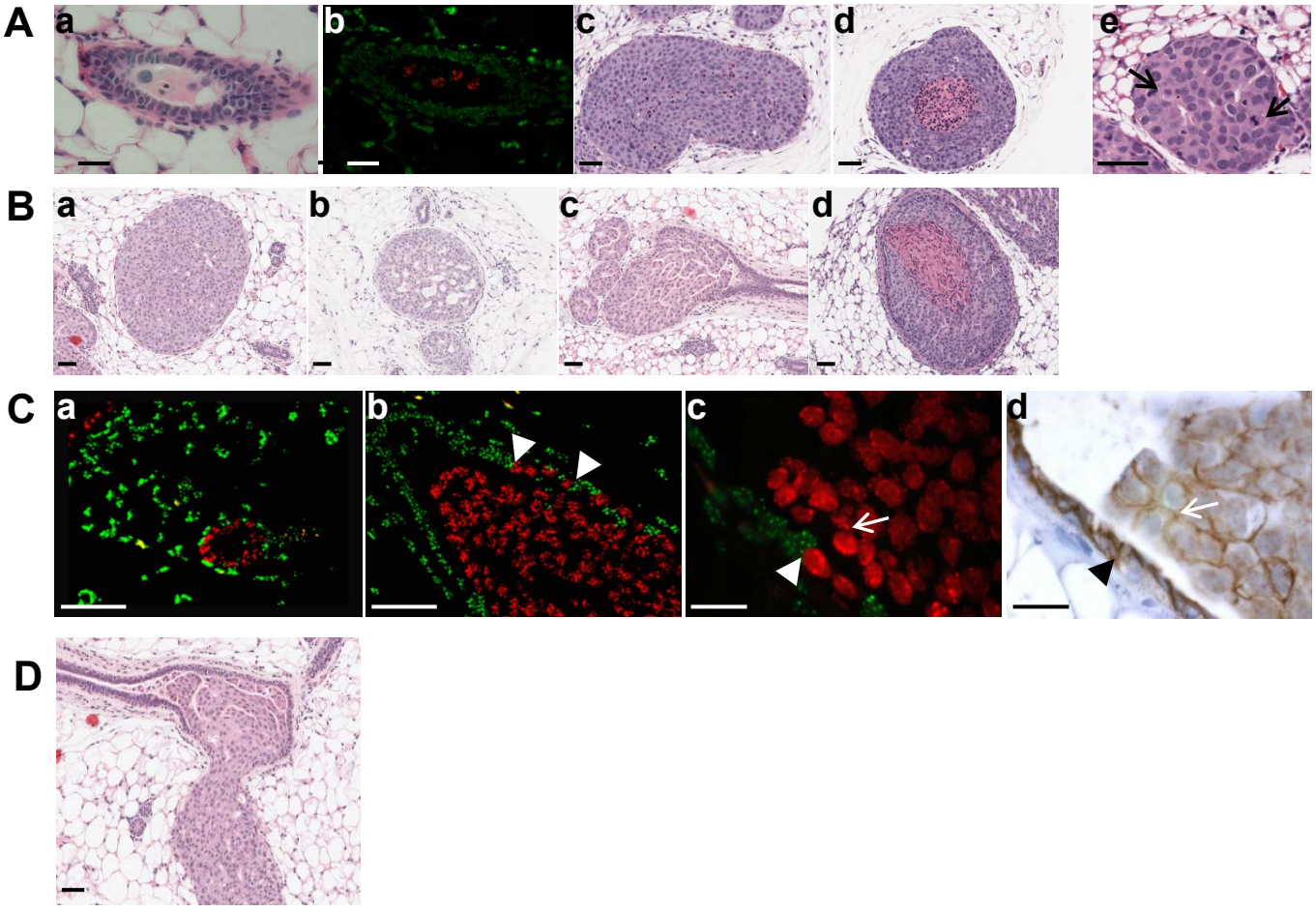

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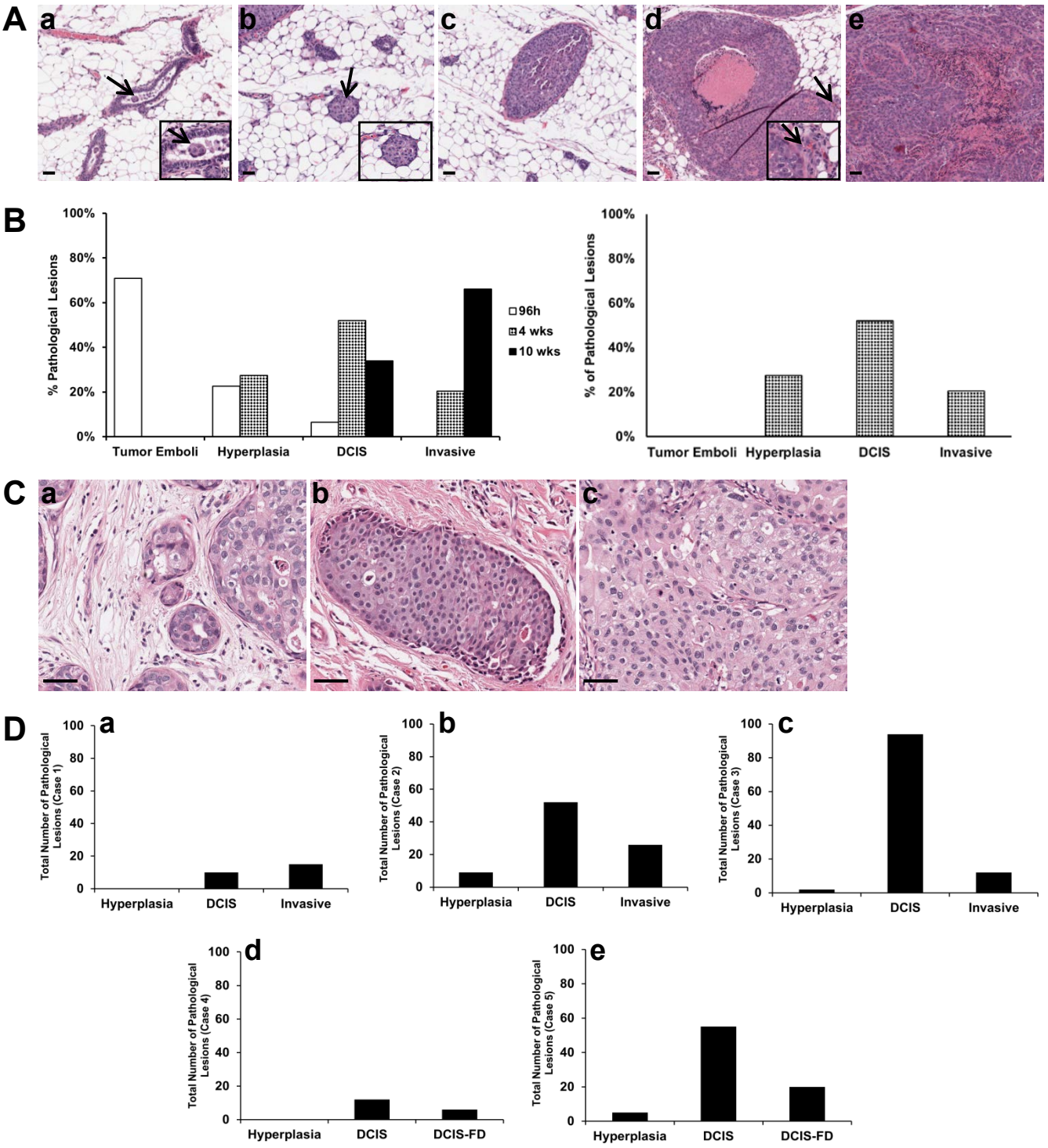
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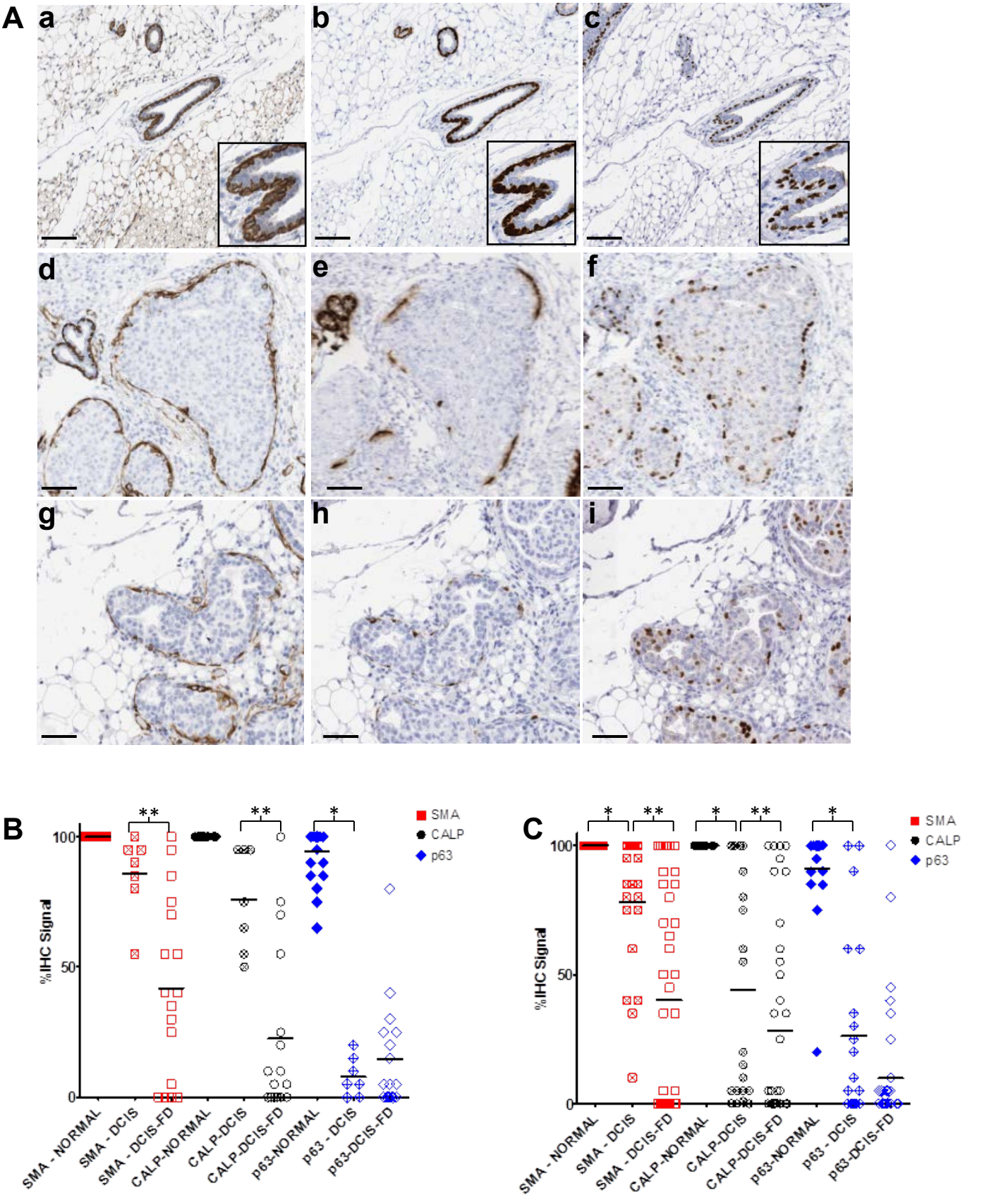
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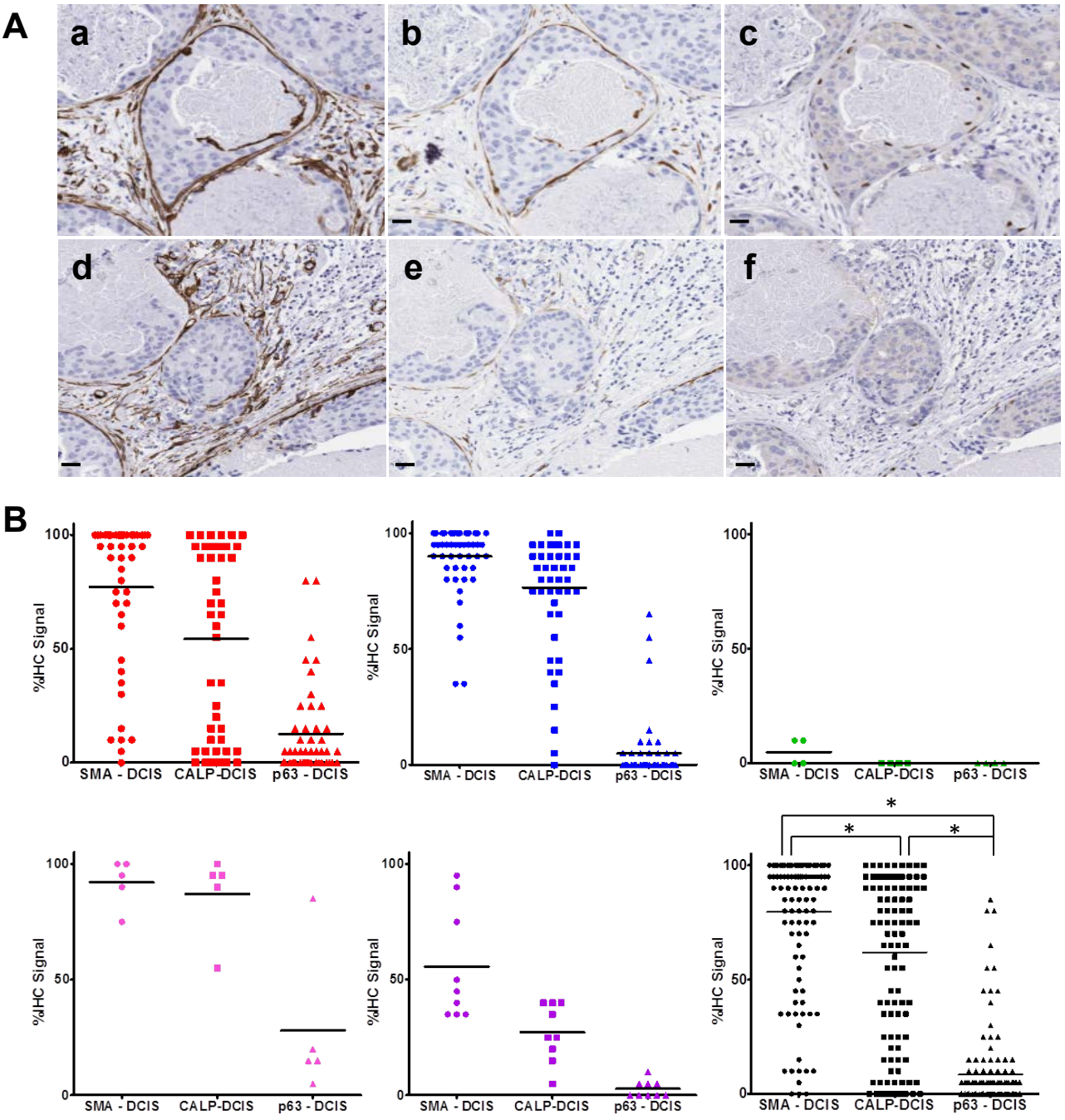

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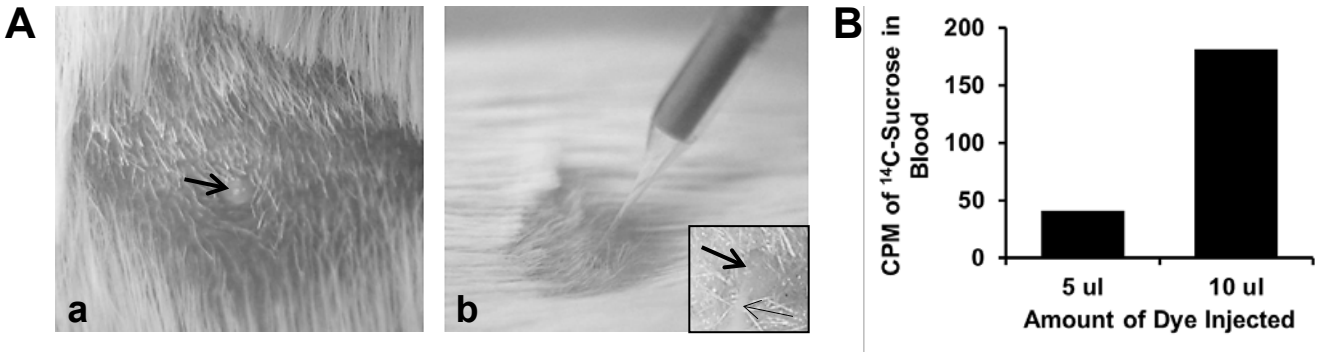

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September 28, 2012

Dr. Lewis Chodosh, Editor-in-Chief
Breast Cancer Research
BioMed Central
236 Gray's Inn Road
London WC1X 8HB
United Kingdom

Dear Dr. Chodosh:

Enclosed please find a manuscript entitled: "A Novel Intraductal Delivery Model that Permits Study of Host Physiology on Human Ductal Carcinoma In Situ Progression" which I am submitting for exclusive consideration of publication as an article in Breast Cancer Research.

The paper demonstrates a novel, non-surgical, mammary intraductal tumor cell delivery model that provides a robust physiologic environment to study early stage human breast cancer progression with respect to changes in the myoepithelium and effects of host reproductive state. Using this model, we demonstrate gradual loss of three myoepithelial cell markers prior to the physical disruption of the myoepithelial cell layer that occurs with progression to invasive disease. To the best of our knowledge, these data represent the most robust characterization of myoepithelial cells with DCIS progression, to date. Further, using this model, we show that intraductal lesions are promoted during postpartum mammary gland involution. Previous studies have demonstrated promotion of tumor cells in direct contact with involution-stroma, which is rich in inflammatory mediators. Our unexpected result that intraductal tumor cells are also promoted during involution suggests unexpected mechanisms of cancer promotion after pregnancy. As such this paper should be of interest to a broad readership including those interested in breast cancer research, preclinical models of DCIS, and the tumor microenvironment.

We have no competing interests to declare.

Knowledgeable referees for this paper might include:

- Daniel Medina [breast cancer/xenograft models of DCIS] (dmedina@bcm.edu)
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- Charlotte Kuperwasser [breast cancer progression and invasion/stromal-epithelial interactions] (charlotte.kuperwasser@tufts.edu)

Thank you for your consideration of my work. Please address all correspondence concerning this manuscript to me at the address stated above and feel free to correspond with me by e-mail (tanya.russell@ucdenver.edu).

Sincerely,

Tanya D. Russell, PhD

TITLE PAGE

Title: A Novel Intraductal Delivery Model that Permits Study of Host Physiology on Human Ductal Carcinoma In Situ Progression

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ABSTRACT

Introduction: We describe a preclinical, mammary intraductal tumor cell delivery model that permits investigation of progression of early-stage breast cancer. Human breast tumor cells are established in the correct anatomical location for ductal carcinoma in situ (DCIS) in the absence of surgical manipulation. This model avoids wound-healing confounders and provides a more physiologic environment.

Methods: MCF10ADCIS.com cells were delivered into the intact mouse mammary teat via intraductal injection and an optimized tumor injection volume identified that did not compromise ductal integrity. To assess influence of host reproductive state on intramammary tumor progression, nulliparous or recently pregnant hosts whose mammary glands were involuting at time of tumor cell injection were utilized. Mammary glands were harvested 4 weeks post-injection, evaluated for tumor histology, tumor growth, and myoepithelial cell layer integrity, using multiple histochemical approaches.

Results: DCIS-like lesions develop throughout the gland with full representation of human DCIS histologic subtypes, which progressed through stages of atypical ductal hyperplasia, DCIS, and subsequent invasive ductal carcinoma. MCF10ADCIS.com cells incorporate into the mouse mammary ducts and form E-cadherin-based junctional complexes with each other and with neighboring normal mouse epithelial cells. Although the MCF10ADCIS.com cell line is characteristically negative for estrogen receptor (ER), progesterone receptor (PR) and Her 2 *in vitro* and *in vivo*, established intramammary tumors were noted to express ER. Progressive loss of myoepithelial cell differentiation markers is also demonstrated, identifying loss of p63 as an early indicator of compromised myoepithelium. Using this model to assess the effects of host reproductive status on DCIS progression, we found an increase in tumor incidence and burden in

the postpartum involution group compared to the nulliparous control group.

Conclusions Our murine intraductal model of human breast cancer provides a rigorous approach to the study of early-stage breast cancer progression and demonstrates the ability to assess changes in the myoepithelium as well as the influence of the host reproductive state on DCIS progression. Since mammary ducts are the primary site of occult tumors in women, we propose that this intraductal model will be a highly relevant for the study of host physiology on human breast cancer progression.

KEYWORDS

murine mammary gland, intraductal, human DCIS, tumor progression, myoepithelial cell, involution

INTRODUCTION

There is clinical evidence for histological progression of breast cancer through atypical hyperplasia, ductal carcinoma in situ (DCIS), invasive ductal carcinoma and metastasis [1]. Histopathologic and genetic progression of epithelial cancers has suggested that acquisition of metastatic potential is a relatively late event. However, microarray data demonstrate that early-stage lesions segregate into those with and without metastatic potential, highlighting the importance of early events in tumor progression [2]. Lack of relevant model systems to investigate early events in tumor cell invasion currently hinders our understanding of breast cancer progression.

The clinical definition of invasive breast cancer is local escape from the confines of the mammary duct into the adjacent tissue stroma. In the normal mammary gland, epithelial ductal and alveolar structures are surrounded by a contractile myoepithelial cell layer which facilitates milk expulsion during lactation [3]. The mammary myoepithelial cells are also required for normal mammary gland development, as they influence epithelial cell polarity, ductal branching and milk production [3]. A hallmark of progression from DCIS to invasive cancer is physical breach of this myoepithelial cell layer. With respect to tumor progression, recent studies suggest that myoepithelial cells play an active role in tumor suppression by secreting protease inhibitors, downregulating matrix metalloproteinases [4-8], and producing tumor suppressive proteins such as maspin, p63, Wilm's tumor 1, p73 and 14-3-3Sigma [7-12]. According to this theory, the tumor suppressive nature of myoepithelial cells is lost with tumor progression, facilitating the transition from a pre-invasive state to invasive cancer [6, 7]. Another hypothesis posits that tumor cells and/or accumulation of other reactive non-epithelial cells, such as fibroblasts or immune cells, lead to the breakdown of the protective myoepithelial barrier and "escape" of

tumor epithelial cells [6, 7, 13]. Studies have reported that DCIS-associated myoepithelial cells are phenotypically different than normal myoepithelial cells [5, 14]; and tumor cells adjacent to focal myoepithelial cell layer disruptions can display distinct phenotypes including estrogen receptor (ER) negativity, genetic instabilities, increased expression of invasion-related genes, and aberrant e-cadherin expression [13, 15, 16]. Overall, these data support the notion that interplay between tumor cells and the myoepithelial cells contribute to loss of the myoepithelial cell layer that is critical for the transition to invasive disease.

Studying tumor progression in the mammary gland is further complicated by the fact that the gland undergoes dramatic functional and compositional changes with hormone exposure, and hormone-driven events such as menarche, menstrual cycling, pregnancy and lactation all impact breast cancer risk in women [17-21]. Evidence that the host reproductive state influences breast cancer progression has been obtained in pre-clinical studies. For example, using 3D culture and mammary fat pad models, we have shown that postpartum involution, a period of active mammary gland tissue remodeling following weaning, creates a wound-healing like microenvironment that is permissive to tumor growth and metastatic spread [22-24]. For the study of early stage DCIS progression, a model that permits assessment of host physiology is lacking.

Tumorigenic potential of human mammary epithelial tumor cell lines is primarily evaluated by injecting cells into the mammary fat pads (MFP) of immunocompromised mice [25]. While the MFP is the correct organ host for invasive breast cancer, it is not the correct anatomical location for early stage, pre-invasive tumors. With respect to tumor progression, MFP models bypass the requirement for tumor cells to exit from the location of their initiation, i.e., the mammary ducts. Alternatively, transgenic models offer correct anatomical location of breast

cancer and display tumor progression from initiation to hyperplasia to invasive stages, but since all epithelial cells contain the active oncogene, these models do not replicate transformation as a rare event. An intraductal approach in the absence of surgery offers a key advantage in that cells are directly placed in the correct anatomical location for tumor initiation, which permits modeling of the natural history of disease progression in the background of normal mammary ducts. Further, this approach permits co-evolution of tumor progression with myoepithelial cell changes as well as stromal changes with minimal wound healing or pro-inflammatory induction.

MATERIALS AND METHODS

Animals

5-week old female SCID mice were obtained from Taconic (Hudson, NY) and maintained in the Center for Laboratory Animal Care at the University of Colorado Anschutz Medical Campus. Females were bred at 8-9 weeks of age as previously described [26] and weaned between 10-14 days post-parturition to initiate involution on the same calendar date. Age-matched nulliparous female mice were used as controls. Intraductal tumor inections were performed as described below. Mammary tissue was excised from animals euthanized by carbon dioxide exposure followed by cervical dislocation. All animal procedures were approved by the Institutional Animal Care and Use Committee of the University of Colorado Anschutz Medical Campus (protocol #72110(07)1E).

Cell Culture

MCF10ADCIS.com cells and GFP-labeled MCF10ADCIS.com cells (a generous gift from Kornelia Polyak) were cultured as previously described [5] and resuspended in PBS immediately prior to injection. Cells were used between passages 8 – 22, as passages later than 22 have been shown to display a more invasive phenotype [27].

Intraductal Injections for Tumor Studies

3-10µl of 50,000 MCF10ADCIS.com cells were intraductally injected into anesthetized mice using a previously described intraductal delivery method developed for viral delivery [28, 29]. Briefly, the end of a 25µl Wiretrol II disposable glass micropipette (no. 5-000-2050; Drummond Scientific Company, Broomall, PA) was drawn and fire-polished into a fine tip of 60-75µm. Sterile cell solution was loaded into the micropipette with a stainless steel plunger. Using a micromanipulator, the tip was gently inserted directly into the teat canal and cells slowly ejected

into the lumens of the left third thoracic and both fourth inguinal mammary glands of mice (n = 3-4 injected glands /mouse). To study the effect of postpartum involution on tumor growth, cells were intradutally injected into mammary glands of involution group mice 2 days post-weaning (n = 2-3 injected glands/mouse) or age-matched nulliparous control group mice (n = 2-3 injected glands/mouse). The third right thoracic mammary glands served as non-injected controls for all injected mice. Images depicting the intraductal injection technique were captured using a Canon PowerShot A620 camera with 4X optical zoom.

Determination of Mammary Ductal Epithelium Permeability

Epithelial tight junction permeability as a function of injection volume was assessed as previously described [29, 30]. Briefly, on the day of sacrifice, 2 μCi of [^{14}C]-sucrose (Amersham, Buckinghamshire, United Kingdom) was lyophilized and dissolved in sterile Trypan blue. Either 5μl or 10μl of this solution was intraductally injected into the 4th inguinal mammary glands of each mouse (n = 2) under anesthesia. 10μl blood samples were taken from the tail vein 5 min after each injection, and the amount of ^{14}C present was determined by liquid scintillation counting.

Immunohistochemistry, Imaging, and Quantification

Excised mouse mammary glands were fixed in 10% NBF, paraffin embedded , and prepared for hemotoxylin and eosin staining as previously described [26]. Briefly, entire histological sections were scanned as described and total tumor number and area were quantified using Aperio Spectrum software (Aperio Techologies, Vista, CA). For immunohistochemistry, 4μm sections of paraffin embedded mouse mammary gland tissue were pretreated with Dako TRS Antigen Retriveal Solution (TRS) or Dako EDTA Antigen Retrieval Solution (EDTA). Research using de-identified human breast tissue as positive IHC controls was conducted under a protocol

deemed exempt from subject consent as approved by the Colorado Multiple Institution Review Board (COMIRB) and tissues were acquired as previously reported [26]. The following antibodies, antigen retrievals, and antibody dilutions were used: mouse anti-human estrogen receptor (ER) (EDTA, 1:100; Leica Microsystems, Inc., Buffalo Grove, IL), mouse anti-human progesterone receptor (PR) (TRS, 1:400; Dako, Carpinteria, CA), rabbit anti-human HER2 (TRS, 1:500; Dako), mouse anti-human e-cadherin (TRS, 1:500; BD Biosciences, San Jose, CA), mouse anti-human p63 (EDTA, 1:200; BioCare Medical, Concord, CA), mouse anti-human cytokeratin 5 (CK5) (EDTA, 1:50; BioCare Medical, Concord, CA), rabbit anti-human calponin (EDTA, 1:800; Abcam, Cambridge, MA), mouse anti-human smooth muscle actin (SMA) (EDTA, 1:200; Dako). ER positivity was assessed according to the Allred scoring method [31]. HER2 positivity was determined using the FDA approved Hercep test for the Dako Autostainer. For myoepithelial cell layer integrity quantitation, tumor associated myoepithelial cell expression of SMA, calponin, and p63 was obtained using serial IHC sections. Data is presented as precent of tumors/group suurounded by ≥50% positivity (arbitrary cutoff), with 25 tumors per group analyzed.

Fluorescent In Situ Hybridization (FISH) Analysis

FISH analyses were performed using probes for human and mouse Cot-1 DNA, as previously described [32], by the University of Colorado Cancer Center Cytogenetics Core.

Statistical Analysis

Statistical significance was determined by Student's t-test where applicable.

RESULTS AND DISCUSSION

Attributes of the Intraductal Model

We focus our analysis using MCF10A DCIS.com cells as a representative human breast cancer cell line capable of forming early stage DCIS-like lesions *in vivo* [5, 27, 33]. Derived from the MCF10AT cell line, these cells meet the criteria for a model of human breast cancer progression as they display histologic progression from hyperplasia to DCIS to invasive carcinoma in subcutaneous, mammary fat pad and intraductal injection models [5, 27, 33, 34]. Here, MCF10A DCIS.com cells were intraductally injected into an intact teat to minimize inflammation induced by surgical manipulations (Figure 1). In nulliparous hosts, the tumor take rate was 65%. Given that progression to invasive disease requires disruption of epithelial junctional integrity as well as loss of the normally protective myoepithelial cell layer, it is imperative that ductal integrity not be compromised during the intraductal procedure. To address this issue, we determined the optimal injection volume to ensure that the technical aspects of intraductal delivery did not disrupt integrity of the mouse mammary epithelial junctional complexes or the myoepithelial cell layer. We employed serial IHC analysis to confirm the presence of GFP-labeled MCF10ADCIS.com cells [24] injected at 2.5 µl, 5.0 µl. or 10 µl volumes (Figure 2A, a,d,g) and the effect of the different injection volumes 24 hours post-injection on the integrity of the epithelial and myoepithelial cell layers using e-cadherin (Figure 2A, b,e,h) and smooth muscle actin (Figure 2A, c,f,i), respectively. Although there was no evidence of GFP positive tumor cells within the mammary stroma at any of the volumes of cells injected (Figure 2A, d,g), we found small areas of epithelial and myoepithelial breakdown (Figure 2A, a-c) at an injection volume of 2.5 µl. These disruptions were not seen at 5µl or 10 µl injection volumes (Figure 2A, d-i). One possible explanation is that delivery of cells in volumes

of less than 5 µl may not allow sufficient dispersion of tumor cells within the ducts, leading to local disruption.

Whether or not junctional integrity is compromised in the nulliparous mammary gland via intraductal injection cannot be fully addressed using IHC. Previous studies have analyzed tight junction permeability of mammary epithelial cells during secretory activation by intraductally injecting ^{14}C-sucrose and measuring its presence in the blood [30, 35]. We assessed ^{14}C-sucrose permeability in nulliparous glands and found that while injected dye volumes of 5 µl do not appear to compromise ductal integrity, volumes of 10 µl or greater may disrupt junctional complexes (Figure 2B). Therefore, for subsequent studies, we elected a 5 µl volume of tumor cells as optimal volume for injecting nulliparous mammary glands.

Our histological data of MCF10ADCIS.com tumors corroborate and extend previous observations by showing intraductal DCIS lesions that display characteristics of the main human DCIS subtypes: solid, cribriform, pseudo-papillary, comedo, and apocrine (Figure 3A, a-e). Further, these tumor cells have the ability to locally invade into adjacent stroma (Figure 3A, f). The distribution of lesions with hyperplasia, DCIS or invasive characteristics (tumor stage) at 4 weeks post injection was 28%, 52%, and 20%, respectively (Figure 3B). Evidence that this phenotypic distribution is due to disease progression is strongly suggested by the observation that at one week post-injection, very few invasive lesions are observed (Figure 3C), whereas later time points more numerous invasive stage lesions are observed (Figure 3A, f).

Unique to the intraductal delivery model, MCF10ADCIS.com cells are observed to form epithelial intraductal hyperplasias (Figure 3D, a) and incorporate into the normal mouse ductal epithelium (Figure 3D, b) as detected by fluorescent in situ hybridization (FISH) analysis with probes specific for human (red) and mouse (green) COT-1 DNA. In agreement with data

obtained from other intraductal models [33], lesions formed from MCF10ADCIS.com cells utilize the endogenous mouse myoepithelial layer (arrows , Figure 3D, a,b), and do not generate a human cell derived myoepithelial cell layer as observed in the subcutaneous and fat pad models [5, 27, 36]. We next evaluated whether these human tumor cells form E-cadherin-based adherens junctions with neighboring mouse epithelial cells within the mammary duct. Formation of adherens junctions would confirm that very early stage tumor lesions develop in the intraductal model, and further, adherens junction presence would permit the evaluation of their disruption with disease progression [37]. Our data indicate that MCF10ADCIS.com cells form junctional complexes with normal mouse epithelial cells, as well as with neighboring tumor cells, albeit at a lower staining intensity (Figure 3E, a). Confirmation that human tumor cells and normal mouse mammary epithelial cells within the duct form adhesion junctional complexes was obtained by serial FISH analysis (Figure 3E, b), and demonstrate the relevance of this model for the study of tumor cell escape/invasion out of the mammary duct.

Our intraductal approach offers an advantage to study host effects on various subtypes of breast cancer. Xenograft tumors formed by MCF10ADCIS.com cells have been previously characterized as estrogen receptor (ER), progesterone receptor (PR) and HER2 negative and positive for the basal phenotype marker, cytokeratin 5 (CK5) [24, 33]. Prior to injection, MCF10ADCIS.com cells express cytokeratin 5 (Figure 4, a), but not ER (Figure 4, b), PR (Figure 4, c) or HER2 (Figure 4, d). Surprisingly, in contrast to a previously described intraductal xenograft model [33] , MCF10ADCIS.com cells injected intraductally re-expressed ER in a subset of cells (Figure 4, f). HER2 status was indeterminate by IHC (Figure 4, h). All staining was confirmed by IHC analysis on respective positive controls (Figure 4, i-l). Although the question of why ER is preferentially re-expressed in MCF10ADCIS.com cells when

intraductally injected is beyond the scope of this present work, it sheds light on the unique nature of this model for the study of host-tumor interactions at early stages of disease.

Characterization of the Myoepithelial Cell Barrier with DCIS Progression

Using a panel of myoepithelial specific markers, SMA, calponin [38-40], and p63 [5, 9, 41], we assessed DCIS lesions to determine if loss of these markers occurs with disease progression. SMA, calponin and p63 expression pattern in normal, non-tumor bearing ducts is evident from staining of mammary tissue (Figure 5A, a, d, g). The myoepithelial cell layer surrounding some DCIS lesions have high levels of all three myoepithelial cell markers, indicating a non-compromised myoepithelial cell layer (Figure 5A, b, e, h). However, many DCIS lesions are surrounded by a potentially compromised myoepithelial cell layer, as evidenced by lower expression levels of these markers (Figure 5A, c, f, i). Quantification of these data show that the myoepithelial cell layer surrounding DCIS-lesions have lower expression of SMA, calponin, and p63 compared to normal ducts (Figure 5B). Additionally, p63 appears to be lost earlier than SMA or calponin, as many myoepithelial layers surrounding DCIS-lesions were SMA and calponin positive, but p63 negative (data not shown). Further, loss of p63 in the myoepithelial cell layer correlated with gain of p63 in the tumor cells (compare 5A h and i). These later data suggest that myoepithelial p63 expression is differentially regulated between myoepithelial cells and tumor cells at the transition to invasiveness. Cumulatively, these studies demonstrate the ability to investigate myoepithelial cell changes associated with DCIS progression using this intraductal model.

Influence of Physiological Reproductive State on Tumor Progression

One strength of an intraductal model in the absence of surgical manipulation is that it permits the non-confounded investigation of host factors on tumor progression. In a xenograft

mammary fat pad model, we have previously demonstrated that the postpartum involuting mammary gland is characterized by a wound-healing like microenvironment that is tumor promotional [23, 24, 26, 32, 42]. An unanswered question is whether the postpartum mammary gland would be similarly tumor promotional for lesions confined within the mammary ducts. Our analysis shows that more tumors form in the involution group (Figures 6A and 6C, b) and these tumors are larger in size (Figures 6B and 6C, b) compared to their respective nulliparous controls (Figure 6C, a). Thus, our intraductal model allows us to assess the effects of reproductive state on DCIS progression to invasion, and demonstrates for the first time, the ability of postpartum involution to influence progression of tumor cells confined within the ducts.

CONCLUSIONS

Our preclinical intraductal model of human breast cancer provides a rigorous approach to study breast cancer progression from early-stage ductal hyperplasia to invasion. An intraductal approach recently described offers a major advancement over MFP models by depositing cells in a large volume (200µl) within the surgically exposed lactiferous duct, which permits lymph node metastasis not observed in MFP models [43]. However, our data using epithelial cell tight junction disruption as a marker for loss of epithelial integrity demonstrate that the normal ductal networks within the mammary gland are likely disrupted with volumes exceeding 10µl, suggesting that the "large volume" intraductal method prohibits the study of early-stage tumor cell incorporation into the ductal lining of the host mammary gland as well as changes in the myoepithelial cell layer with tumor progression. Another intraductal model injects a small volume of tumor cells unlikely to compromise duct integrity, but surgical manipulations are used to cleave the teat and expose the main lactiferous duct [33]. These surgical procedures may induce localized wound-healing and inflammatory programs, which have been shown to be tumor promotional in other contexts [44-47]. In this report, we describe an intraductal model that minimizes wound-healing programs and inflammation, and which permits the evaluation of subtle physiologic changes in tissue remodeling without the confounder of wound-healing programs associated with surgical manipulation or physical duct disruption. A limitation to the method described here, and all other human tumor models, is the requirement for immunodeficient animals. The application of our intraductal model utilizing isogenic mammary cancer cell lines that reflect the biologic subtypes of human breast cancer would permit investigation of DCIS progression in an immune competent host.

Surprisingly, ER is re-expressed when MCF10ADCIS.com cells are intraductally injected into mouse mammary glands (Figure 4). This inherent plasticity of human breast cancer cell lines can cause a conundrum for developing intraductal models to study the influence of breast cancer biologic subtype on progression from DCIS to invasive cancer. However, additional studies with multiple cell lines are to needed to determine if the re-expression of these markers is cell line specific or more generalizable. Nevertheless, human versus mouse myoepithelial derivation between xenograft and intraductal models may influence stem/progenitor characteristics of MCF10ADCIS.com cells. For example, in vitro studies characterize MCF10ADCIS.com cells as bipotential progenitors, and xenograft studies show that these cells differentiate into both luminal and myoepithelial cells when injected subcutaneously or into the MFP [5, 27, 36]. Our data corroborate recently reported studies showing that MCF10ADCIS.com cells delivered intraductally utilize mouse myoepithelia [33]. In the intraductal model, it is possible that ER+ MCFDCIS10A.com cells may derive from progenitors that are influenced by ER+ mouse luminal cells and or stem cell niches within the host mammary ducts [48]. Further work is needed to explore these possibilities.

Our model also permits a rigorous evaluation of the effects of DCIS progression on molecular changes in the myoepithelium, which serves as a barrier to invasive cancer. Our data suggest that this protective layer is compromised during early stages of tumor progression. We focused our initial studies on three myoepithelial cell markers: SMA, calponin, and p63, loss of which is commonly used to identify DCIS progression to invasive disease [49-51]. SMA positivity surrounding tumors remains relatively stable (Figure 5, a-c), suggesting that the actin biostructure detected with anti-SMA antibody may be a myoepithelial barrier lost later DCIS progression. Calponin, an important actin cytoskeleton regulator [52-54] and tumor suppressor in

human leiomyosarcoma [54] also appears to remain stable surrounding DCIS lesions (Figure 5, d-f). We show that p63 expression appears to be lost prior to that of SMA and calponin, and may indicate compromised barrier function in myoepithelial cells. However, intratumoral p63 is also evident in DCIS lesions formed by MCF10ADCIS.com cells, indicating acquisition of basal-like attributes with progression (Figure 5a, i). Upregulation of p63 in DCIS lesions formed by MCF10ADCIS.com cells has been previously shown to be near regions of compromised myoepithelium [36]. These data suggest the use of p63 as a myoepithelial marker may not give an accurate analysis of myoepithelial integrity from tumors with a basal phenotype.

Further, we demonstrate proof-of-principal that host physiology can influence DCIS progression, identifying this model as relevant for addressing key questions such as influence of host reproductive status on breast cancer progression. Emerging work from our laboratory in multiple animal models of postpartum breast cancer shows that the microenvironment of the involuting gland is highly supportive of tumor cell dissemination and metastasis [23, 24, 55]. The development of this new intraductal model will permit a more physiologically relevant investigation into the interactions between reproduction state and DCIS progression. Future studies include further evaluation of the effect of host reproductive state on tumor suppressive related myoepithelial cell markers.

In summary, our preclinical intraductal model of human breast cancer provides a rigorous approach to studying tumor progression from early stage intraductal hyperplasia to invasion. This model is particularly suited to studying host effects on DCIS progression. Since occult tumors in women develop within ducts, we propose that this teat injection model will facilitate research of early disease progression, a requisite for research focused on breast cancer prevention and inhibition of local invasion.

ABBREVIATIONS:

DCIS	ductal carcinoma in situ
ER	estrogen receptor
MFP	mammary fat pad
FISH	fluorescent in situ hybridization
SMA	smooth muscle actin
CK5	cytokeratin 5

COMPETING INTERESTS: We have no competing interests to declare.

AUTHORS' CONTRIBUTIONS

TDR designed and performed all animal experiments, performed the intraductal injections, IHC, ^{14}C-sucrose experiments, interpreted and analyzed data, and prepared the manuscript. PS supervised the project, designed experiments, interpreted results, and made substantial contributions to manuscript preparation.

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FIGURE LEGENDS

Figure 1. Intraductal injection method. A small area surrounding the teat (arrow) was aseptically cleared of fur (A). A fabricated glass micropipette with 60-75µm tip diameter was then positioned near the intact teat (B) and carefully guided into the teat (C, arrow). Image in C was taken through the eyepiece of a dissecting scope at 4X magnification.

Figure 2. Ductal and myoepithelial cell layer integrity is not compromised by intraductal injection of 5.0 µl volumes. A. GFP-labeled MCF10ADCIS.com cells were injected at volumes of 2.5 µl (panels a-c), 5.0 µl (panels d-f), and 10 µl (panels g-i) to assess epithelial junctional complex and myoepithelial cell layer disruption. Serial sections were stained with GFP to confirm the presence of human tumor cells (brown, panels a, d, g); e-cadherin (eCAD) to assess ductal epithelia junctional complex disruption (brown, panels b, e, h); and smooth muscle actin (SMA) to assess myoepithelial cell layer disruption (brown, panels c, f, and i). Insets in panels a-c are enlarged to show detail of compromised ductal areas. Images scanned using Aperio software. Digital resolution = 0.25µ/pixel. Scale bar = 100um. B. Ductal epithelia tight junction permeability as a function of volume was assessed by intraductally injecting mice with the stated doses of Trypan blue dye mixed with [^{14}C]-sucrose in nulliparous mice. Each bar represents the average of [^{14}C] counts per minute (CPM) measured in the blood. n = 2/group.

Figure 3. DCIS characteristics of MCF10ADCIS.com cells. A. Hemotoxylin and eosin (H&E) analysis of nulliparous mouse mammary glands injected with MCF10ADCIS.com tumor cells via intraductal method. Tumors formed from MCFDCIS10A.com cells display the different

characteristics of human DCIS (solid – a; cribriform – b; pseudo papillary – c; comedo – d; apocrine – e), and progress to locally invasive disease (f). Images scanned using Aperio software; digital resolution = 0.25µ/pixel. Scale bar = 80µm. B. Distribution of tumor stage in nulliparous mammary glands intraductally injected with MCF10ADCIS.com cells. C. Representative H&E image of a non-invasive MCF10ADCIS.com tumor bolus (arrow) formed 8 days post injection. Image scanned using Aperio software; digital resolution = 0.25µ/pixelScale bar = 60µm. D. Fluorescent in situ hybridization (FISH) analysis for human (red) and mouse (green) COT-1 DNA reveals tumor progression from hyperplastic alveolar nodules (a) to DCIS (b) with incorporation of human tumor cells into normal mouse mammary ducts (circle). Arrows indicate myoepithelial cells. Magnification = 40X. Scale bars = 40µm. E. Serial analysis of epithelial cell junctional integrity. Left panel: IHC analysis of the cytoplasmic domain of E-cadherin (brown). Right panel: FISH analysis of human (red) and mouse (green) COT-1 DNA. E-cadherin-based junctional complexes form between MCF10ADCIS.com cells (white arrows) and between MCF10ADCIS.com cells and mouse ductal epithelial cells (arrowheads). Magnification = 100X. Scale bar = 10µm.

Figure 4. MCF10ADCIS.com cells re-express estrogen receptor in vivo. Serial analysis of MCF10ADCIS.com cells prior to intraductal injection demonstrating triple negative characteristic of these cells (panels a-d) and ER+ tumors formed 4 weeks post-intraductal injection (panel f). Insets in panels f-h are enlarged to show detail of CK5 (e), ER (f), PR (g), and HER2 (h) staining. Positive normal mammary gland (i) and breast tumor (j, k, l) controls are stained for CK5 (i), ER (j), PR (k), and HER2 (l). Images scanned using Aperio software. Digital resolution = 0.25µ/pixel. Scale bar for panels a-d = 50µm. Scale bar for panels e-l = 50µm.

Figure 5. IHC Analysis Suggests Progressive Loss of Myoepithelial Cell Differentiation Markers. A. Serial IHC analysis of myoepithelial cell markers SMA (brown, panels a-c), calponin (brown, panels d-f), and p63 (brown, panels g-i). Insets in panels a, d, and g are enlarged to show detail of normal mouse ductal structures. Some tumors show no apparent loss of myoepithelial cell layer markers (panels b, e, h) while other tumors display loss of these markers (panels c, f, i). Gain of p63 by tumor cells is also apparent (panels h, i). Images scanned using Aperio software. Digital resolution = 0.25μ/pixel. Scale bar = 100 μm. B. Quantification of percentage of tumors surrounded by ≥50% (arbitrary cutoff) myoepithelial cell layer marker, compared to the percentage of normal, non-tumor bearing ductal structures surrounded by ≥50% myoepithelial cell layer marker.

Figure 6. Use of the intraductal approach to analyze physiological impact of reproductive state on tumor progression. Tumor bearing mammary glands from nulliparous and involuting mice were assessed for number and size of tumors using Aperio digital software. A. Total numbers of tumors from each group. The involution group (n = 2) had more tumors than their respective nulliparous control group (n = 1). B. Tumors from the involution group were larger than their respective nulliparous control. Error bars = SEM. C. Representative H&E stained images from nulliparous and involution group tumor bearing mammary glands. Images scanned and tumors measured using Aperio software. Digital resolution = 0.25μ/pixel. Scale bar = 70 μm.

HOST REPRODUCTIVE HETEROGENEITY DETERMINES PROGNOSIS OF YOUNG WOMEN'S BREAST CANCER

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Tumor heterogeneity, and the recognition that diagnosis of breast cancer encompasses many entities, have provided new insights into the complexity of breast cancer causation and progression [1]. With the identification of molecular variability comes new opportunity for targeted and individualized breast cancer treatment. The biological basis of tumor heterogeneity is largely explained by diversity in driver mutations [2]. A further layer of complexity with known prognostic significance, and which is gaining in recognition, lies in the tumor microenvironment [3]. However, host heterogeneity is a prognostic feature of breast cancer in need of greater attention. While some aspects of host heterogeneity, dominantly ethnicity, are recognized clinically and represent active areas of research [4], consideration of parity status as a prognostic feature is under recognized. Importantly, women diagnosed postpartum have worse prognosis than age-matched, nulliparous women or women diagnosed during pregnancy [5], and represent ~40% of all young women's breast cancer. In our Colorado Cohort, a pregnancy within the 5 years preceding diagnosis is an independent risk factor resulting in a ~3-fold increase in death, regardless of tumor biologic subtype. These observations identify a host state, the postpartum window, as an under-recognized prognostic factor in young women's breast cancer.

We have proposed that postpartum breast involution is the dominant window of risk for breast cancer progression associated with pregnancy [6]. In rodents and humans, characterization of the mammary gland during postpartum involution identifies wound healing and immune suppression programs that share similarities with microenvironments known to promote cancer initiation and metastasis. For example, monocytic immature myeloid cells (iMCs) ($CD45^{+}CD11b^{+}GR1^{int/lo}F4/80^{+}$) capable of functionally suppressing T-cell activation *ex vivo*, are present at high levels in the involuting gland. Further, we show that postpartum involution drives tumor progression in three independent rodent models. Importantly, treatments with NSAIDs ibuprofen or Celecoxib, limited in duration to the involution-window, suppress deposition of pro-tumorigenic fibrillar collagen and tenascin-C, while also decreasing tumor growth, tumor cell dispersion and metastasis to the lung [7]. Our most recent data shows that lymphangiogenesis is increased during postpartum involution, providing a possible explanation for the increased metastasis observed in patients diagnosed postpartum. This involution-induced lymphangiogenesis is suppressed by Celecoxib, and postpartum tumors from the Celecoxib treated group displayed reduced lymphovascular density and lymphovascular invasion, data consistent with suppression of metastasis. Cumulatively, our data show upregulation of pro-tumorigenic COX-2 during normal postpartum mammary gland involution, identifying a potential target for the treatment of postpartum breast cancers. The question of whether an NSAID based intervention study could be aimed at recently pregnant women at high risk for postpartum breast cancer remains to be determined, but given the ~ 6 million pregnancies in the US per year, is a highly desirable objective.

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A Novel Mammary Intraductal Delivery Model that Permits Study of Human Ductal Carcinoma In Situ Progression

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Young African American women have an increased risk of developing aggressive forms of breast cancer (i.e. triple negative/basal-like) than young non-Hispanic white women. Recent epidemiological data show increased risk of basal-like breast cancer with increased childbearing in African American women (Millikan et al 2008; Palmer et al 2011). Breast cancers associated with a recent pregnancy (pregnancy-associated breast cancer) are more likely to be metastatic (Lyons et al 2011). We predict that the triple negative/basal-like breast cancer subtype is promoted by a recent pregnancy, accounting in part, for the poor prognosis of young African American breast cancer patients.

We have developed a murine intraductal mammary model to examine the effect of host reproductive status on the progression of early stage human breast cancer. Our model delivers human mammary tumor cells directly through the intact mouse teat into the correct anatomical location for ductal carcinoma in situ (DCIS) without surgical manipulations. MCF10ADCIS.com (triple negative/basal cell line) or HCC70 (triple negative cell line derived from a young African American woman) cells were delivered into the mammary gland via intraductal injection to assess influence of host reproductive state (nulliparity, pregnancy, active post-partum involution) on tumor progression.

Lesions from both cell lines displayed the full representation of human DCIS histologic subtypes, which progressed to DCIS through an atypical ductal hyperplasia stage. Although the MCF10ADCIS.com cell line is typically triple negative *in vitro* and other *in vivo* models, established tumors in the intraductal model were observed to re-express estrogen receptor. HCC70 tumors maintained the triple negative phenotype in our model. Using the MCF10ADCIS.com model to assess the effects of host reproductive status on DCIS progression, we found tumor burden in the pregnancy group was not significantly different than nulliparous controls. Within the pregnant group, tumors appear to be less proliferative and have slightly lower ER expression than nulliparous control tumors. Tumor burden in the postpartum involution group is significantly greater than the respective nulliparous control group; however, the Ki67 proliferative index is lower 4 weeks post injection in comparison to nulliparous controls. DCIS progression to locally invasive disease occurred with progressive loss of myoepithelial cell differentiation markers. In both cell line models, the loss of p63 was identified as an early indicator of compromised myoepithelium. Further, our data suggest that the protective myoepithelial cell layer may be preferentially compromised by tumors formed in postpartum involuting mammary glands.

Our murine mammary intraductal model of human breast cancer provides a rigorous approach to study early stage-tumor progression, and is well suited to study the effect of the host reproductive state on DCIS progression. Since occult tumors in women develop within ducts, we propose that this teat injection model will aid research of early disease progression, a requisite for research focused on breast cancer prevention and inhibition of local invasion. Further, this model may provide a unique opportunity to address and study tumor growth disparities among African American and non-Hispanic white women.

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Title: COX-2 inhibitors target multiple pro-tumorigenic pathways involved in metastasis of postpartum breast cancers.

Women diagnosed as late as ten years postpartum have worse prognosis than nulliparous women or women diagnosed during pregnancy, and represent ~40% of all young women's breast cancer. We propose that breast involution following pregnancy is a window of risk for breast cancer progression. In rodents and humans, characterization of postpartum involution identifies tissue remodeling that shares similarities with microenvironments known to promote cancer initiation and metastasis. Collagen bundles similar to those observed in invasive tumors are found in the involuting gland as well as abundant macrophages with similarities to tumor associated macrophages. In three mouse models of post-partum breast cancer, involution drives cancer progression. To determine whether involution-macrophages could be targeted for prevention or treatment of postpartum breast cancer, macrophages were depleted from actively involuting glands. Surprisingly, macrophage depletion blocked programmed cell death of the mammary epithelium, demonstrating that interventions targeting macrophages in the postpartum setting need to proceed with caution. Conversely, inhibition of COX-2 with NSAIDS did not interfere with postpartum lobular regression in two rodent models. In a xenograft breast cancer model using MCF10A.DCIS cells, COX-2 inhibition with ibuprofen or Celecoxib suppressed collagen deposition during involution and decreased tumor collagen deposition, growth, local tumor cell dispersion and lung metastasis. Celecoxib treatment also suppressed lymphangiogenesis, which occurs at elevated frequency specifically during postpartum involution. High lymphatic vessel density (LVD) and invasion of peritumor lymphatics (LVI) are both poor prognostic factors for breast cancer patients and postpartum tumors from the celecoxib treated group displayed reduced LVD and LVI in the peritumor region. Our studies indicate distinct but inter-related roles for COX-2 in the postpartum setting. COX-2 activity within the tumor cell is required for tumor cell invasiveness and COX-2 activity in the host promotes collagen fibrillogenesis and lymphangiogenesis, both of which provide a permissive environment for tumor cell metastasis. The question of whether an NSAID based intervention study could be aimed at recently pregnant women at high risk for postpartum breast cancer remains to be determined, but is an extremely desirable objective given that the ~ 6 million pregnancies in the US per year. Funded thought grants from the DoD, ACS, and Susan G Komen and Avon Foundations.